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War and the Journal

MOST scientific journals have been affected by the War in at least two ways—a serious decline in foreign subscriptions has reduced income, and the volume of scientific material demanding publication has diminished. These two results tend to counterbalance each other to some degree in affecting finances, the loss in subscription income being partially offset by savings in printing costs.

The Editors of this Journal have not as yet observed any trend toward a decrease in the flow of important optical literature which should be published. During the past few years the Journal has been forced to expand its covers until the amount of material which it carries annually is double that which appeared in each volume a few years ago. Thus the publishers now find themselves furnishing subscribers with twice as much material as formerly at no increase in subscription price. This desirable result would normally be entirely feasible, for during the period of rapid growth of the Journal the membership of the Optical Society has almost doubled, and many new non-member subscribers have been added, so increase in quantity has reduced unit costs.

Now, however, losses in foreign subscriptions and increased prices on labor and materials make necessary an increase in dues to members if the annual budget of the Society is to be balanced during the coming year. A few weeks ago the Directors voted to increase the subscription price of the Journal to non-members by one dollar. Then, on October 29, after a careful study of the budget, the Board voted a corresponding increase in membership dues for 1943.

Members of the Society will, after January 1, 1943, pay dues which are one dollar more than at present. Thus the dues for Associate Members will be $6 and for Regular Members $8.50. Inasmuch as the membership application blank used during 1942 states that the membership dues for associate members shall be $5.00, the Board of Directors has ruled that the increase in dues shall not apply to new applications received by the Secretary prior to December 31, 1942, for Journal subscriptions to begin on January 1, 1943.

So that this relatively modest increase will suffice to balance the budget of the Society, the Directors have decided to reduce slightly the quality of the paper used in printing the Journal, though this paper will still be equal to the best used by other journals in the field of physics. The number of extra copies of each Journal issue printed for later sale will be reduced also. Both of these economies are necessary to avoid a larger increase in dues.

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Inter-Society Color Council Symposium

Color in Art Education

THE aims and purposes of the Inter-Society Color Council are to "stimulate and coordinate the work being done by the various societies, organizations, and associations leading to the standardization, description, and specification of color, and to promote the practical application of these results to the color problems arising in science, art, and industry." Thirteen national associations are now member bodies of the Council and support its activities.

The following four papers were prepared for the Technical Session of the Council's eleventh annual meeting held at the Metropolitan Museum of Art in New York City on February 26 and 27, 1942. At this meeting, the Council for the first time devoted one of its sessions to color problems connected with art, rather than with problems more closely connected with science or industry. The papers discuss problems important to art education, and in their preparation the Council had the generous and enthusiastic cooperation of several leaders in color in the field of art education. The committee, in addition to the Vice Chairman and the Secretary of the Council, consisted of Byron G. Culver and Milton E. Bond of the Art School of the Rochester Athenaeum and Mechanics Institute; E. Blanchard Brown of the Rhode Island School of Design; James C. Boudreau of The Art School, Pratt Institute; Frank J. Allen of the Massachusetts School of Art; Elizabeth Burris-Meyer of the School of Fashion Careers; and Harold C. Parks, Chairman of Delegates from the American Artists Professional League.

The original plan was to select topics under which factual material could be presented, and to have each paper prepared jointly by an art-educator and a technical color worker. As often happens, the complete plan was not followed, but it is believed that many of the deviations are improvements. This meeting was a first venture, and ISCC officers and counsellors hope that cooperation on technical color problems of the artist, such as brought the American Artists' Professional League into Council membership in 1941, the first member body representing art interests, will more and more enable the Inter-Society Color Council to fulfill its aims and purposes in relation to all three of the fields in which color problems are important: science, art, and industry.

In addition to the Technical Session of papers, there were exhibits. Four schools—The Rhode Island School of Design, Pratt Institute, Cooper Union, and the Colorado State College of Education—prepared for exhibit examples of work that would demonstrate the approach to teaching color used in their schools. These exhibits were explained and discussed by representatives of the four schools at a School Exhibits Session held especially for that purpose. The information and points of view expressed by these four representatives round out very well those given in the papers of the Technical Session. Accounts of the school-exhibits discussions have accordingly been prepared and are available in mimeographed form as a supplement to this Symposium on Color in Art Education.

DEANE B. JUDD, Chairman,
Inter-Society Color Council.

Emotions *Versus* Measurement in Teaching Color

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(Received August 17, 1942)

TRADITIONALLY, it is held that the artist arrives at the solution of his problems through "sensing" rather than through reliance upon scientific law or principle. He has, it is believed, a "feeling" for color relations, a "sense" of balance, and a condition of being in "vibratory" harmony with complex rhythms. He frequently does things he cannot explain; in fact, he sometimes resents inquiry, regarding art as a matter of the emotions, not subject to analysis or rationale. That, in brief, is the traditional view, but it is probably far from being truly representative of the professional artist.

In the first place, many effective and accomplished artists do not rely upon emotional guidance to the exclusion of scientific knowledge regarding color and design. One of the greatest contemporary still life painters possesses a familiarity with the chemistry of pigments and aging processes equal to that possessed by the college chemistry professor. My esteemed colleague, the late Grant Wood, approached every stage of the building of his composition with the same slow, careful, painstaking thoroughness characteristic of the laboratory scientist. In the better art schools, effort is made to keep abreast of the latest advances in research.

In the second place, problems in composition are frequently so complicated that final reliance upon anything but over-all judgment is out of the question. But the significant point is that the mature artist, in doing so, is using a trained and disciplined mind which long ago passed through stages of preparation for this very event. Those stages involved the solution of similar problems yielding experience applicable to the complex structure now before him; in fact, the early training thoroughly mastered now serves to simplify and facilitate the complex ordering of line, form, and color, permitting him to dispose of the problems with a readiness which may easily be mistaken for emotional "sensing." Yet throughout the process there is, or was at some time, ordered thinking and logical processes.

In the teaching of color, scientific data, which is simply tested and ordered knowledge, offers much to the serious-minded art student, who should learn all he can concerning the systems of mixing colorants, the theories of color, and perhaps even the measurement of color sense-quanta. These considerations have been, or will be, dealt with by others. In this paper I shall propose two experimental procedures adaptable to art school facilities which are deemed of possible value in the teaching of color.

Experimental studies by psychologists on color preferences,[1] on the apparent "weight" of colors,[2] on size and weight,[3] and on attention value[4] have not been of immediate use to art education. Some have yielded negative findings, others inconclusive results; most of such studies must be limited in their findings to the small population sample of the laboratory. They are also of restricted value because they employ color in abstract isolation, whereas in use it occurs in a setting, the ensuing relationship in each case being of such importance as to condition the response in each instance. The work in binary combinations of colors and that on brightness combinations[5] go little farther than to suggest that the preferences refer back merely to the preferences for the individual components. The studies of appropriateness of single colors

[1] E. J. G. Bradford, "On the aesthetic value of the perceptive types in color appreciation," Am. J. Psychol. **24**, 245 (1913); J. P. Guilford, "The affective value of color as a function of hue, tint, and chroma," J. Exper. Psychol. **17**, 342–371 (1934); also Psychometrika **4**, 1.

[2] J. E. DeCamp, "The influence of color on apparent weight," J. Exper. Psychol. **2**, 347 (1917); M. Monroe, "The apparent weight of color and correlated phenomena," Am. J. Psychol. **36**, 192 (1925); B. C. Koch, "The apparent weight of colors," Contributions in Psychology, Number 9 (The Ohio State University Press, Columbus, Ohio, 1928).

[3] E. J. Warden and E. L. Flynn, "The effect of color on apparent size and weight," Am. J. Psychol. **37**, 398–401 (1926).

[4] M. Luckiesh, *Light and Color in Advertising and Merchandising* (Van Nostrand, New York, 1923); C. A. Morris, "What color shall the free booklet have?" Printers' Ink Monthly **19**, 124–125 (1929).

[5] L. R. Geissler, "The affective tone of color combinations," in *Studies in Psychology: Titchener Commemorative Volume* (Wilson, Worcester, 1917) pp. 150–174; John T. Metcalf, "Pleasantness of brightness combinations," Am. J. Psychol. **38**, 607–23 (1927); B. C. Koch, *ibid.*

and color pairs for specific uses suggest interest for art education and yield some measurement, though indecisive, on the associations found between colors and various purposes involved in their use, and the relative strength of these associations.[6] The lack of great certainty in the associations, suggests, in lieu of more convincing evidence, that associations of color with human experience lack sufficient universality to be dependable except in the instances usually advanced in psychologies of art and other treatises.[7] The few constancies reduce chiefly to such experiences as the universality of viewing blue in the sky and on reflecting surfaces as bodies of water; blue-green and yellow-green in the vegetation of habitable areas; and the less frequently experienced spot and transient contacts with red and yellow.[8]

In addition to these constancies arising from uniform experience in which nature provides the basic stimuli, a considerable number of color contexts enter into widespread cultural practice and may be mistakenly presumed to be universals. Greenish-yellow is, in American culture, a less-preferred color to other colors such as red or blue-green. The basis for this evaluation lies in the fact that greenish-yellow has consistently been associated with filth, disease (jaundice, yellow-fever, quarantine), and cowardice. Language responses have tended to reinforce the emotional conditioning, as have also mimetic responses involving olfactory and other experience. But with other peoples and cultures, yellow, only slightly removed, has been a sacred hue. Similarly, white runs the gamut of symbolizing purity and saintliness to the white flag of abject despair and surrender.

Insofar as art may be projected chiefly for a given culture or population segment, it will devolve upon the person to judge the relative constancy of the color associations involved in his problem. Upon this judgment will depend the relative success of the emotion-inducing properties of the colors used, upon the type of public for whom the picture is intended. It will be found that the nearer the assumed associations are to the general properties of the psychological primaries, the more likely his presumption is apt to meet with widespread and certain response.

Since color preference is essentially an individual matter and art is intrinsically a social matter, it is easily probable that two aspects of research have been neglected. Great art is usually conceived as appealing to an universal public, not limited in space or time. Great art, however, is rare. Most art, indeed, most contemporary production, has reference to a contemporary public and, in the instance of industrial art, segments of contemporary society. Industrial design, advertising art, architecture, and interior design need to know contemporary taste of the segment involved, which may be severely limited or so broad as to approximate universality.

It would hence seem logical that research procedures already available may be adapted or combined to yield guidance for workers in color and in the teaching procedures of art education. This aspect discloses the necessity for taking into account taste preferences of the segments concerned. This can be accomplished by scientific sampling methods widely used in market research and public-opinion surveys.

The second neglected aspect lies in the fact that the study of color employing patches of colored paper, each of equal size, not only introduces inaccuracies attributable to difficulties in control of material and lighting, but also this presentation of equal areas, while desirable from the experimental viewpoint, does not closely relate itself to the actual use of color in art and industry. Seldom does one use equal areas of two colors; large areas of color are more usual with small areas of another color, as in a trim or in accents.

A methodology is proposed uniting three procedures that could yield data on color preference for binary combinations of variable magnitude, data on samplings of specific publics, and group tendencies in preferences of these publics. The methodology should be of use both in commercial practices and in art education.

The apparatus involved, similar to one used in the Psychological Laboratory of the Uni-

[6] N. Collins, "The appropriateness of certain color combinations in advertising," unpublished thesis, Columbia University (1924).

[7] M. Graves, *The Art of Color and Design* (McGraw-Hill, New York, 1941).

[8] N. C. Meier, *Art in Human Affairs* (McGraw-Hill, New York, 1942).

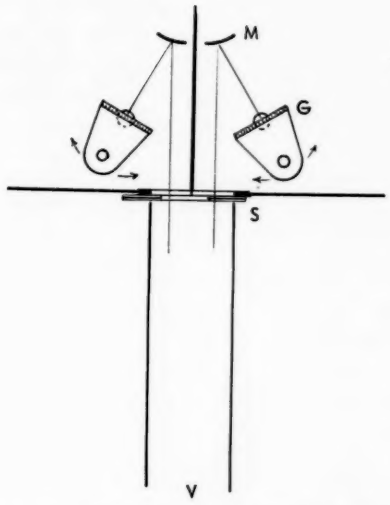

FIG. 1. Projected apparatus. *M*—convex mirrors; *G*—gratings on rotatable mounts; *S*—synchronized shutters; *V*—viewing position.

versity of Toronto,[9] ideally would utilize spectral color originating from gratings and projected from two positions, one on either side of the subject, so arranged that by mirror deflection the projected color from both appear in the subject's line of regard. (See Fig. 1.) By means of synchronized aperture-control, it is possible to introduce one of the colors as a ground color and then, as a variable, a color first seen as a mere point. The variable color may then be made to displace more and more of the ground color at the will of the subject, until the preferred balance or point of maximum pleasantness is reached. Another color is then introduced as the variable color. The procedure continues until all the colors involved have been seen in variable relation to every other color, following the paired comparisons formula.[10]

Since the judgments of a single subject represent merely that person's preferences at the single occasion of making the judgment, it has validity and interest only in the improbable instance that this individual should represent the median taste of the general population, or in the likewise improbable circumstance that it represent the median judgment of the artistically competent. It need be taken into account, however, that, if industry or art education should deem it expedient or desirable to know what color combinations are most generally pleasing to the general population or to the artistically competent statistical "universe," either may be determined approximately by combining the procedure with sampling methods[11] and running the sample through the apparatus.

The identification of a sample of the artistically competent is perhaps more in point for our consideration, and will be outlined in brief. Statistics of grade records, results of aptitude tests, and so forth, in art schools, would provide preliminary sources of information as to the identity of available representatives of the class and their proportion to the current population of successful artists. The numerical and age aspects of competence could be derived from directories of artists. The sample would thus be computed from this information, making the ratio representative of age, sex, artistic interests, and distribution. The size of the sample would be in accord with the degree of accuracy needed. For most practical purposes, a sample of perhaps fifty would be adequate.

A second adjunct to the teaching and study of color under control is possible through the use of a color composition apparatus such as that devised and constructed in the Art Psychology Laboratory of the University of Iowa.[12] This apparatus (see Fig. 2) is essentially a device for applying fixed and variable color through controlled illumination to objects and settings and for effecting fusion of the setting with supplementary backgrounds projected from the rear onto a translucent screen. When viewed from in front, or when picked up by color photography, the ensemble is seen as a homogeneous composition. By means of five sensitive auto-transformers controlling batteries of the primary colors, *n* variations of these colors may be produced; likewise, *n* variations of them in combinations. There are also flood and pencil-

[9] E. Baker, "Spectrally pure colors in binary combinations," University of Toronto Studies, Psychol. Ser. 2 (1902–1907).

[10] J. P. Guilford, *Psychometric Methods* (McGraw-Hill, New York, 1936).

[11] Bernoulli. In H. L. Rietz (ed.), *Handbook of Mathematical Statistics* (Houghton Mifflin, Boston, 1924).

[12] N. C. Meier, and W. A. McCloy, "An instrument for the study of creative artistic intelligence," Psychol. Monogr. 48 (1938).

FIG. 2.

spot accessory sources, with or without gelatine color screens.

This apparatus is adaptable to a variety of purposes: the study of object color, color mixtures, absorption, reflection, diffusion, accent, mood, and creative imagination in the organization of the whole composition. Summer landscape lighting and coloring may be experimented with in winter. Changing mood with the same object-material in neutral gray clay may be produced at will, and an entire composition may be planned experimentally in color before it is attempted in sketch or at the easel. The composition may be produced in different palettes, as it were, each in turn photographed in Kodachrome and studied at length before any painting is undertaken. The apparatus has value both as an instrument for individual trial-and-error planning of compositions and also for class or group demonstration of color properties and color phenomena.

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Color-Mixing Systems

Color *vs.* Colorant Mixture

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(Received August 17, 1942)

AS artists, designers, teachers, and laymen, we are interested in color as a *sensation*, but since there can be no standardized psychological system of color organization and notation without some sound physical basis, we had best turn to what the physicist has done for us through the aid of scientific investigations and instruments, particularly in methods of exact charting of color and color-mixture by graphic means.

It is easy to inquire, "What is the best color system," but the answer must depend upon the purpose for which it is to be used. Color-mixture systems are represented on diagrams; think of them as color maps. You would not ask for a best map of the geographical world, expecting to have everything on it, for you know that there are all kinds of maps for representing the earth's surface, each made for a specific purpose.

Some of the early color maps are those developed by philosophers and physicists early in the last century. Many of them are like early world maps that are historically interesting because one can see how each worker added something here, something there.

Ostwald, in Scott Taylor's translation of *Colour Science*,[1] has developed a brief history of many of the contributions of past workers; he goes back to the Greeks and the Romans; to Goethe who collected but never completed material for a history of color; to Newton who found that sunlight could be broken up into separate colors; to Le Blond who first used Newton's seven colors (about 1730) for color

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[1] Wilhelm Ostwald, *Colour Science*, trans. by J. Scott Taylor, Vol. 1 (Winsor and Newton, Ltd., London, 1931).

prints and found later that he could obtain the same result with three; to Gautier his competitor who arrived at an identical solution about the same time; to Dufay who, about 1737, described how dyeing of yarns and fabrics could be done with three colors; to J. Brenner who published a Color Table in 1680 in Stockholm, giving a list of the coloring matters then known; to R. Waller who in 1689 made a color chart with washes of color; to Tobias Mayer, who made charts of all combinations obtained to 12 steps on a basis of a red-yellow-blue triangle, with several charts for black and white combinations; to J. H. Lambert who made a pyramid by pigment mixtures, based on Gamboge, carmine, and Prussian blue; to Ph. O. Runge, the painter, who added the idea of decreasing to black as well as to white, the basis for his sphere; to Chevreul, chemist and dyer of the famous Gobelin Works, who, although he contributed nothing new to mixture problems, created much interest and called attention to problems of simultaneous contrast. Ostwald points out that Lambert, Runge, and Chevreul recognized the three-dimensional nature of color, that Runge clearly grasped that black and white are independent colors (Mayer and Lambert not quite sure), but Chevreul not at all. Up to this time no workers attempted to produce or suggest a measured system.

In 1810 Goethe published his *Farbenlehre*. Schopenhauer, a pupil of Goethe's, laid emphasis on cerebral activity in color experience. Two generations later Hering repeated the physiological part of the work, and Ostwald himself used portions of this theory in his "doctrine of semichromes." Helmholtz (1821–94) added the conception of additive and subtractive mixture, and determined complementaries. Young, in 1807, contributed the theory that there is a red, green, and violet receiving mechanism in the retina, and Helmholtz developed this theory further. Grassman formulated the laws of color mixture. James Clark Maxwell needed measurement, so he used disks, applied Grassman's laws, and found equations that held, and that colors mix on straight lines of junction in a color-mixture triangle. Hering, 1834–1918, turned to psychological analysis and inquired into "experience" of colors, not into the spectrum. Schultze in 1866 suggested that rods and cones might have different functions, the rods to distinguish light-to-dark, the cones to distinguish all color differences including light-to-dark. But Helmholtz paid no attention to this theory. Later von Kries and Parinaud advised the same theory, and more recently E. Müller; it is now generally accepted. To this list must be added the names of Brewster, Scottish scientist, author of the red-yellow-blue theory that unfortunately has been so widely used in the American educational system; of Rood, an early American color scientist, who suggested the use of a double cone, following on the ideas of Lambert and Runge; of Ladd-Franklin who so capably championed her theories of color vision; of Frederick E. Ives, father of modern color printing; of Munsell, who added measurement and standardized charts for demonstration of a color notation; of Troland, whose interests lay in psychophysical problems, of those who developed Technicolor, Kodachrome, and other processes of modern color photography; of Hecht in his physiological studies of vision; and of many a worker in the National Physical Laboratory of Great Britain and in the National Bureau of Standards of this country who did the careful and tedious work that necessarily preceded the adoption, in 1931, of data to represent a standard observer for colorimetry, standard illuminants for colorimetry, standard observing conditions, and a standard coordinate system.

If, today, for color-mixture problems we had to recommend a single map, we would of course consider the one that gives us the maximum information with the minimum of disadvantages. Therefore our choice today would be the one internationally adopted in 1931 by the International Commission on Illumination, known in this country as the I.C.I. system,[2] and in very general use among all technical color workers. Perhaps some day we shall have a still better color-mixture map, but now, in 1942, we would

[2] Proceedings of the Eighth Session, Commission Internationale de l'Éclairage, Cambridge, England, pp. 19–29 (September, 1931); T. Smith and J. Guild, "The C.I.E. colorimetric standards and their use," Trans. Opt. Soc. (Eng.) **33**, 73 (1931–32); D. B. Judd, "The 1931 I.C.I. standard observer and coordinate system of colorimetry," J. Opt. Soc. Am. **23**, 359 (1933); A. C. Hardy, *Handbook of Colorimetry* (Technology Press, Cambridge, Massachusetts 1936).

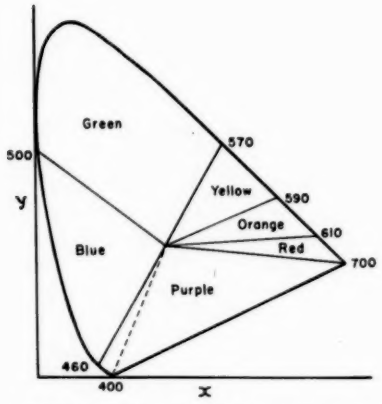

FIG. 1. I.C.I. (x, y) diagram. The locus of spectrum colors is indicated by the horseshoe curve beginning at 700 millimicrons at the red end of the spectrum, passing through the orange, yellow, green, and blue portions to 400 millimicrons. The non-spectral region which contains the purples is enclosed by a straight line joining the ends of the spectrum.

select the 1931 I.C.I. mixture diagram as the best method for studying color-mixture.

The I.C.I. mixture diagram is a map, just like any other map. The type of I.C.I. diagram most often used in the past 10 years is the so-called (x, y) diagram, and although color has three coordinates, by this method only the fractional parts x and y need to be plotted since $x+y+z$ always add to a total of 1.0. The color coordinates on the I.C.I. (x, y) diagram may be compared therefore to the latitude and longitude of geographical maps. If we plot the I.C.I. (x, y) measurements of the pure spectrum colors, wave-length by wave-length, as carefully measured in the laboratories of the physicist, we shall find a boundary which describes the limit of real colors. The visible spectrum arranges itself in horseshoe fashion, as may be seen by examination of Fig. 1, with red, 700 millimicrons in wave-length, at one end, passing through orange, yellow, green, blue, to a very purplish-blue at 400 millimicrons in wave-length. Those colors that do not occur in the spectrum, the purples of the non-spectral region, are enclosed by the straight line connecting the red and the far blue of the spectrum. Within these boundaries all real colors may be plotted. But just as certain types of projections exaggerate certain areas of the earth's surface on world maps, so this diagram exaggerates certain color differences. If you will think of the spectrum for a moment, you will recall that it is not divided into equal hue areas; the yellow and orange bands are very narrow in relation to the red. If you will look at the spacing on this diagram for the areas marked red, yellow, green, blue, and purple, you will see that they occupy areas that exaggerate the greens and minimize the reds. On this map the neutral point, although it may shift freely with change in illuminant, is for ordinary observing conditions near to equal parts of x and y and z. This plots it at $x=0.333$, $y=0.333$. As measured from the neutral point out to a point at which a straight line intersects the line enclosing all real colors, it is easy to see that relative saturations are not accurately represented in accordance with visual experience, since the line to green is much longer than that to red. Yet full red has a higher saturation than full green.

But this is not a diagram to foretell visual appearance, it is a color-mixture map, developed to plot and foretell color mixtures; and on this map all color mixtures lie in straight lines.

This diagram is also useful for other purposes: we can record many kinds of color data, notations, specifications, and gamuts of color. For instance, if we want to standardize the Munsell system,[3]† or the Ostwald,[4] we measure the individual color samples and plot the resulting (x, y) data on this type of diagram. This has already been done for the complete Munsell system and for some of the Ostwald samples. Data of this sort indicate the contour or limit of the equal chroma samples of the Munsell system when those samples all have equal Munsell value. We have to make the limit of "equal Munsell value" or "equal lightness," because this I.C.I. diagram does not allow us to distinguish between colors of different lightnesses. This takes us back to our geographical map: elevations are not usually apparent from a road map. Similarly, two colors, one light and

† See footnote references and bibliography in reference 4.

[3] James J. Glenn and James T. Killian, "Trichromatic (I.C.I.) analysis of the *Munsell Book of Color*," J. Opt. Soc. Am. **30**, 609 (1940).

[4] Milton E. Bond and Dorothy Nickerson, "Color-order systems, Munsell and Ostwald," J. Opt. Soc. Am. **32**, 709 (1942).

one dark, that may have identical (x, y) values, will differ; they will have neither the same lightness nor the same saturation. They will have the same "purity," for the points at which they are plotted are equally displaced from the neutral point toward the spectrum locus on the diagram. But the light color may look twice as strong in saturation as the dark color. This is an important difference, and is the reason for keeping our color language consistent. When we think in terms of color mixture and the I.C.I. diagram we may speak of dominant wave-length, luminance (luminous apparent reflectance), and purity.** These are psychophysical terms because *color mixture* is a psychophysical matter. When we speak of color as we see it, in terms of *color organization* as opposed to *color mixture*, we may speak in terms of hue, lightness (value), and saturation (chroma).** These are psychological terms, for seeing color is a psychological matter. There is a relation between the two sets of terms but it is not so simple as the uninformed often assume.

Ordinarily we think of colors as belonging to surfaces, but there are times when we cannot tell whether a color comes to us from a reflecting surface or through a filter placed over an aperture light source. For example, if you place a piece of red paper behind a slightly recessed hole in the black front surface of a box with internal illumination, you may find observers quite unable to tell whether the red comes from a surface or through a filter or even from a red light inside the box.

A point on the I.C.I. diagram would represent the chromaticity of the red. This (x, y) specification of the light that reached our eyes; it is a specification of the *quality* of that light. A specification for *quantity* of light is also necessary and this is expressed in terms dependent upon the mode of appearance of the color. The (x, y) diagram adequately specifies only the chromaticity of a sample.

** Terms from OSA Colorimetry Committee Report, now in preparation. This report will contain definitions, also a table, showing the relation between the terms used to describe the color stimulus (physical), color (psychophysical), and the color sensation (psychological). Color mixture is a psychophysical matter; color organization is a psychological matter. There is no attempt in this paper to touch upon spectrophotometric methods for studying the color stimulus (physical).

The purpose of the foregoing example is to show that *color is the property of light that reaches our eyes*. We can make a filter take on a surface appearance; or, we can take a surface color and make it modify light like a filter.[5] It is obvious therefore that no distinction between surface colors and aperture colors is necessary as far as chromaticity is concerned. It is better to think of both surface and filter as modifiers of the original light, even though they modify it by entirely different methods. It does not matter how we create the modifiers; they are simply a means for changing the light to get the effect we want.

This approach to the subject has been made in order to indicate that there is only one kind of color, and consequently there can be only one kind of color mixture. A specification of the quality of light is the specification of its color, and such a view makes the problem of color mixture easy to understand.

The I.C.I. system and diagrams developed from it are developed to foretell color mixture, and on such diagrams all color mixtures lie in straight lines. If we plot points to represent red and green on this diagram, Fig. 2, and draw a straight line between them, that line will represent all possible mixtures of those two colors. Yellow lies

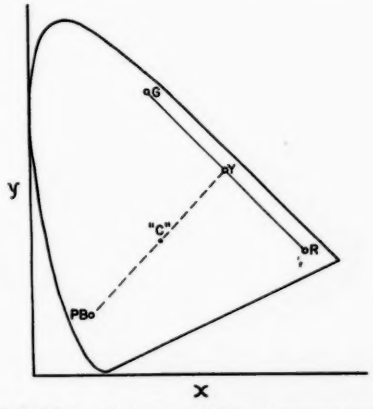

FIG. 2. I.C.I. (x, y) diagram. Color mixtures always lie on straight lines on this diagram. The line of mixture for red and green passes through yellow. The line of mixture of yellow and purple-blue passes through the neutral point, indicated on this diagram by the point representing I.C.I. Illuminant *C*.

[5] David Katz, *The World of Colour*, trans. by R. B. MacLeod and C. W. Fox (Kegan Paul, Trench, Teubner and Company, London, 1935).

on that line. Let us try out mixtures of red and green to see if they result in yellow. Try it with lights, as with green and red spotlights. The result is yellow. Next, let us plot points to represent blue and yellow on the same diagram. On a line connecting those points all colors resulting from their mixture will be represented. The line goes through, or nearly through, the neutral point of the diagram. If we try out the mixture with lights, as with filtered spotlights, the result will be neutral, or some color represented on the line drawn on the diagram depending upon the proportion of each light used in the mixture.

Other forms of color mixture can be described in a similar manner. For example, if we have Maxwell disks, the color of the mixture of two disks is determined in the same manner. It is only necessary to draw a straight line connecting two points on the chart which represent the disk colors, and the mixture colors—no matter what their proportion—will be represented by a point on this line. The use of more than two colors in the disk mixture is merely an extension of this fundamental principle. In a multicolored design whose elemental color areas are small so as to be beyond resolution at certain distances, the apparent color may be predicted by the method described above, or by means of rotating sectored disks.

If we were required to choose three lights which, when mixed together, would give a maximum gamut, the choice would be made by means of this mixture diagram. As may be seen from the shape of the boundary colors, the three colors which would best satisfy this requirement would be red, blue, and green, since points representing these colors define a triangle which encloses the gamut of color obtainable by mixtures. If we do not confine our discussion to the combination of positive amounts of light, we find that any three colors will do (providing only that no two will match the third), for if we are permitted to use negative amounts of these (a simple process in the laboratory) we then can match all colors. Any three lights, no two of which will match the third, can be called primaries in a color-mixture system. The reason that red, blue, and green are in common use is that they include the greatest gamut in positive mixtures. This is extremely convenient for many reasons.

The most important commercial application of these primaries is in color photography. A photograph of the subject is made through each of three filters, red, green, and blue, and positives made from these separation negatives are placed in three projection lanterns together with their respective taking filters. The projected images when superimposed on the screen provide a color reproduction of the original subject. The various densities of the separation positives control the amount of the red, green, and blue primaries which mix to reproduce the original colors of the subject. While this is not the method in common use today, it, nevertheless, demonstrates the principle underlying color photography.

These, then, are the fundamentals of color mixture. But you ask, and you may well ask, since you work with colorants: How about paint mixtures—pigment, dye, and ink mixtures? The answer is: *Colorants merely control light.* This is important: *COLORANTS MERELY CONTROL LIGHT.*

Any mixture of colorants is merely a means to produce a desired color. All colorant mixtures or gamuts are unique, and are controlled by factors which have no relation to color mixture. For example, in modern color photographic processes requiring a single projection device or where colored photographs are obtained as prints, the red, green, and blue primaries are controlled by blue absorbing, green absorbing, and red absorbing colorants. These colorants are chosen on the basis of how well they control the primaries and how complete a color gamut is within their range. The three colorants that are used look like magenta, yellow, and blue-green. They may be in the form of dyes when they are used in photographic emulsions, or they may be in pigment form when used in an artist's palette, or in printing inks as used for the colored illustrations in magazines.

Just as three colorants control the light primaries in color photography, so all colorants control light in a general sense. Whenever paints, pigments, dyes, or inks are used, they act as modifiers of the light under which they are viewed. They should not be judged on the basis of their apparent color, but only on a

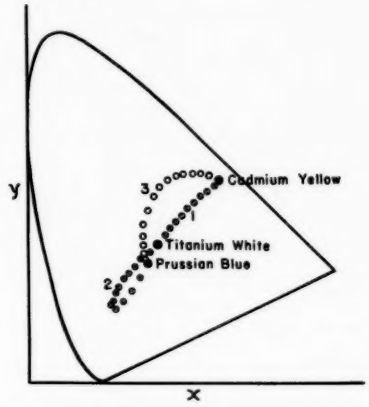

FIG. 3. I.C.I. (x, y) diagram. Colorant mixtures indicated by the gamuts for cadmium yellow and titanium white (see reference 2), Prussian blue and titanium white (see reference 2), Prussian blue and cadmium yellow (see reference 3). Each pair of colorants is a case by itself; sometimes such mixtures are near to straight lines, sometimes they are far from straight lines. Colorant mixtures can be predicted only on a basis of experience.

basis of what each contributes to the desired result.

No exact forecast, no plotting of the result of colorant mixtures (often called "subtractive" mixtures) can be foretold from the color of the components alone. They cannot be predicted in the exact manner of color (or "additive") mixtures. There are many specific peculiarities —selective absorption, refractive index, particle size, etc.—and most of the trouble in understanding this subject of colorant mixture has occurred because broad, general assumptions have been made, and have been assumed to be as rigorous as are the rules of color mixture. Until new and untried colorants are found not to fall into happenstance categories, the artist and art teacher often fail to realize the difference between the nature of *color mixture* and *colorant mixture.*

The easiest and most satisfactory way to study the mixture of colorants is to make the mixtures. (Certain physical data, the absorption and scattering coefficients of colorants, are of extreme value in predicting a gamut, but their consideration is a technical study in itself.)

If, for instance, we are working with pigments, and select those that give complete hiding films, a good mixture example would be that of cadmium yellow and titanium white. After making chips in a sufficient number of steps to represent various proportions of these pigments, we would have actual evidence of the color gamut possible with these two materials. If we then evaluated, or measured, the chromaticity of the chips and located them on the I.C.I. mixture diagram, as in Fig. 3, we would see in just what way the colorant mixtures varied in chromaticity, and how close or far the gamut of the colorant mixture departs from the straight line that can be predicted for color mixture. Another representation is shown in Fig. 4 for this same gamut. This time we have departed from the (x, y) mixture diagram in order to see how the color of the mixture decreases in purity as the mixture increases in luminous reflectance.

In the case of colorant mixtures of Prussian blue and titanium white on the (x, y) diagram, Fig. 3, the mixtures with the first small amount of white show an increase in purity of color, and not only do they increase in purity, but they swing slightly toward a more purplish blue, until a maximum purity is reached, then the mixtures turn back toward the green-blue as the mixtures approach a maximum of white-pigment content. Another representation of this color gamut is shown in Fig. 4 in order to illustrate how an increase in purity accompanies an increase in luminous reflectance up to a certain proportion of the two colorants, then there is a decrease in purity as the reflectance is further increased.

Prussian blue should not be called an opaque pigment in the sense that cadmium yellow or titanium dioxide white are called opaque, but it does a good job of hiding the support on which it is applied, because of its considerable absorption of light. If the film is applied over a white reflecting surface, and successively reduced in thickness, another color gamut is produced which may look similar to the one produced before, but is not exactly the same. In fact, we can take two different Prussian blues, which might have the same mass-tone, and from them produce entirely different color gamuts on extension with the same opaque white or by film thickness variations.

The mixture of Prussian blue with cadmium yellow offers further interesting results which,

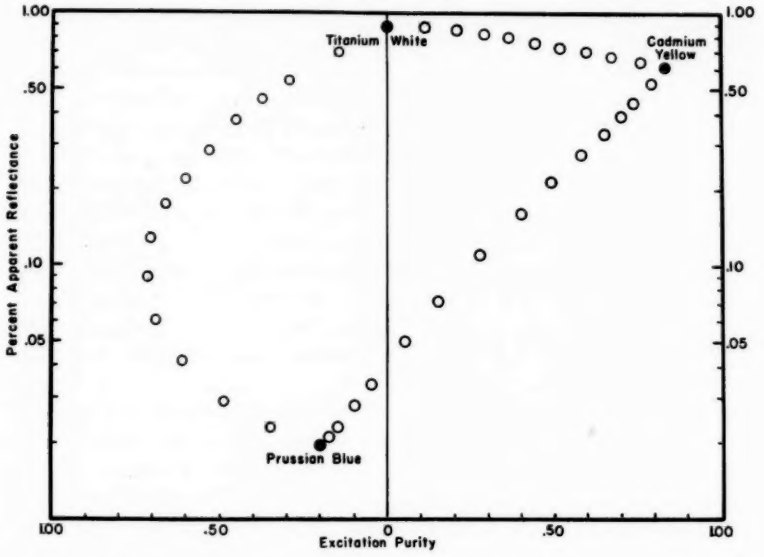

FIG. 4. The three gamuts illustrated in Fig. 3 are shown on a different type of diagram in order that changes in reflectance and purity may be made apparent. It is evident that colorant mixtures cannot be relied upon to mix in straight lines. The shape of colorant mixture curves cannot be predicted except upon the basis of experience with the particular colorants involved.

because of the wide variations in color attributes, are difficult to visualize except with a three-dimensional model. Reduced to two dimensions the chromaticity is shown effectively on the I.C.I. diagram, Fig. 3.

Once the picture is clear in our minds of the way in which color gamuts are apt to depart from the straight line relations of color mixture, it will be evident why attempts at simplification lead only to confusion. All mixtures of colorants should be considered special cases since that is what they actually are. Any similarity to the accurate and simple rules of color mixture is purely accidental.

Until we know pigments through experience with their mixtures, or through knowledge of their spectral absorption and scattering coefficients, we do not know what will happen nor the rate at which it will happen.

Perhaps it is as well that colorant mixtures do call for experimentation, for too many people want only a formula or recipe to produce any required result. In the teaching of color and design there has been too much of a tendency to rely upon formulas, many instructors referring to so-called "laws," in an attempt to arrive at some sure-fire way of creating eternal beauty. Many of these theories have long since been outmoded in the light of scientific investigation; many are as yet scarcely formulated; most of them deal with the subject in the abstract and have absolutely no bearing or influence upon the arts as they are lived and practiced. Formulas may well serve as the life-giving foundation and structure of science, but they are the assassins of an imaginative, creative, and vital art. They should be so recognized by the artist and the art educator, and used as an intelligent means to orient—not to substitute for—the creative impulse. An understanding of color mixture and of colorant mixture, with the consequent ability to plot and plan at arriving directly at the goal should be to the artist what the ability to make and read maps is to the explorer. If the explorer knows his goal, and has all these modern aids, they help him to reach his goal with a minimum of wasted effort.

Color-Order Systems, Munsell and Ostwald

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ALTHOUGH artists have used colors for thousands of years, not until the last century did man begin to conceive of his color sensations as something apart from light and from pigments, dyes, filters, and so forth. Then he began to see that pigments, dyes, and filters are modifiers of light, that they are colorants which help to produce color sensations by means of light. Early charts and systems were arranged according to the results obtained when he mixed his common pigments, as in placing orange opposite blue and placing yellow as the complement of violet. Then, almost suddenly, he discovered that intimate patterns of intermingled colors might give a completely different color sensation to the observer than would pigment mixtures of those same colors. He noticed that orange and blue pigments when mixed on a palette tended to neutralize one another without much change of hue, but that mixtures made by painting or weaving orange and blue shapes in small juxtaposed areas tended to retain a considerable degree of saturation with a decided alteration of hue, in some cases becoming strong magenta! So he began to ask, is it more important to arrange my color ideas according to the results of pigment mixtures or according to the results obtained through pattern and other retinal mixture devices?

We have then, in our modern color systems, three things to think about: the colorant, which modifies or alters light by transmission or reflection; the light itself which may or may not be altered; and the color sensation which results from the action of the light on the eye. The color results of colorant mixtures are not very dependable; they cannot be predicted from the colors of the components. Yellow and blue colorants usually produce green but they may produce red! But the result of color mixture, whether obtained by means of juxtaposed or superimposed lights, or of painted, dyed, or printed areas of juxtaposed color (common usage in all graphic and plastic art expression), is completely dependable.

There are now several systems of color order based on the visual relationship of colors, rather than on the painter's palette, or on the physical measurement of light alone. Of these, two are very useful to the art teacher because they are well illustrated by carefully prepared charts. They are the Munsell[1,2] and Ostwald systems.[3,4] The Munsell system was developed in this country early in this century, the Ostwald system in Germany during the years of the first World War. Each has had a growing appeal; each has had considerable study by the scientist as well as the artist.

Neither the Ostwald nor the Munsell system disputes the importance of systems that help to understand or predict either color or colorant mixtures; one must of necessity know these things. The one thing that both Munsell and Ostwald insist upon is that the study of color as sensation, in art use, shall be based on an orderly arrangement of the visual attributes of color, independent of colorants or light.

THE OSTWALD SYSTEM

It may be interesting first to know something of Wilhelm Ostwald himself. He was born in Riga, Latvia, in 1853. As a chemist (Nobel prize winner in 1909) he always had an interest in artists' materials. He was an amateur painter, author of a series of "Letters to a Painter,"

[1] A. H. Munsell, *A Color Notation* (Munsell Color Company, Baltimore, Maryland), 8th edition, edited and rearranged, 1936.

[2] A. H. Munsell, *Color Diary*. Bibliofilm Document No. 1307 ($2.50) obtainable from the American Documentation Institute, 2101 Constitution Avenue, Washington, D. C.

[3] Wilhelm Ostwald, *Colour Science*, (2 vols.), translated by J. Scott Taylor, also *Colour Album*, arranged by J. Scott Taylor (Winsor and Newton, Ltd., London), Vol. I, 1931, Vol. II, 1933, *Colour Album*, 193–.

[4] Wilhelm-Ostwald- Archiv, "Schriftenverzeichnis zur Farblehre," Grete Ostwald; Theodor Martins Textilverlag (Leipzig, 1936), (List of Ostwald's writings on color).

published in an English translation in 1906. In 1905, while in this country to give a series of lectures at Columbia, Harvard, and the Massachusetts Institute of Technology, he met A. H. Munsell, and because of his interest in color he went to Munsell's studio, in fact used the Munsell sphere and early charts in one of his M.I.T. lectures. But in 1905 the charts of the Munsell system were merely in skeleton form, and it is doubtful whether Ostwald had any

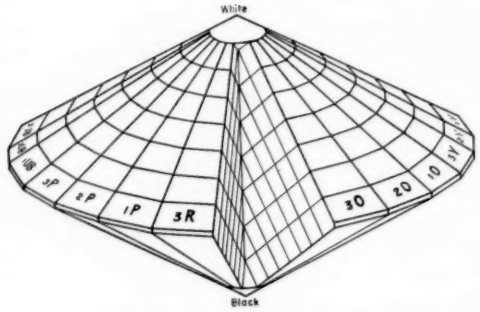

FIG. 1. Ostwald's color solid, a double cone. First and second *red* section removed.

realization of the thoroughness of Munsell's work. It is certain, for example, that he had no idea that the Munsell value scale already had been adjusted to perceptually equal steps, an adjustment which Ostwald later found necessary to build into his own system by resorting to the Fechner law, much as Munsell had done.

Not until Germany became involved in the first World War did Ostwald, who was then 61 years old, find time for color research. Because of the war, he was cut off from extensive correspondence, and therefore developed his color system without the advice that he undoubtedly would otherwise have sought. This is undoubtedly the reason that he developed his system without reference to principles which form the basis of the intensive studies even then being made in the official standardization laboratories of the United States, Great Britain, and his own country.

Ostwald graphically represents his concept of the classification and organization of all colors as a double cone solid, Fig. 1, on and within whose surfaces are represented all visual variables. (As is elsewhere pointed out, the practical solid varies from this ideal.) On the equator are placed the saturated hues. The core of the solid is a scale of neutral grays progressing from white at the top to black at the bottom. In the development of this scale he first mixed black and white on a color top but soon realized that any black paper contained some white. He then invented a photometer which enabled him to compare a painted sample of gray with a standard white sample viewed in controlled amounts of light, thus measuring the percent of reflectance. Next he produced a painted scale which illustrated diminishing reflectance in a regular arithmetical progression downward, that is, by tenths, when measured on this photometer. To his dismay, it did not look as it should, for a loss of one-, two-, and three-tenths of white made little difference between the samples, and even a loss of nine-tenths was still far from black! While pondering over this he remembered the Fechner law, and proceeded to make a new series of grays in which the white decreased in a

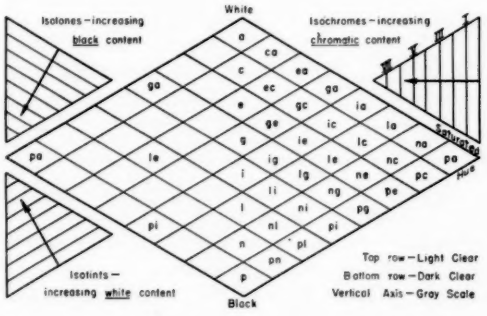

FIG. 2. Vertical cross section of Ostwald solid, showing complementary monochromatic triangles. Boundaries are regular since maximum saturation for each hue is placed at *pa* position. Isotones, isotints, and isochromes are shown by direction of arrows.

geometrical ratio. This scale, now in use, appeared to him to have equal steps. It is measured in the unequal percents of black and white shown in the spaces of Fig. 3. He gave to this scale an alphabetical notation from *a* to *p* (white to black). In modern use intermediate steps are usually omitted. It should be noted that in this figure and on his charts the ideal white and black cannot be included but rather the practical colors limited by obtainable

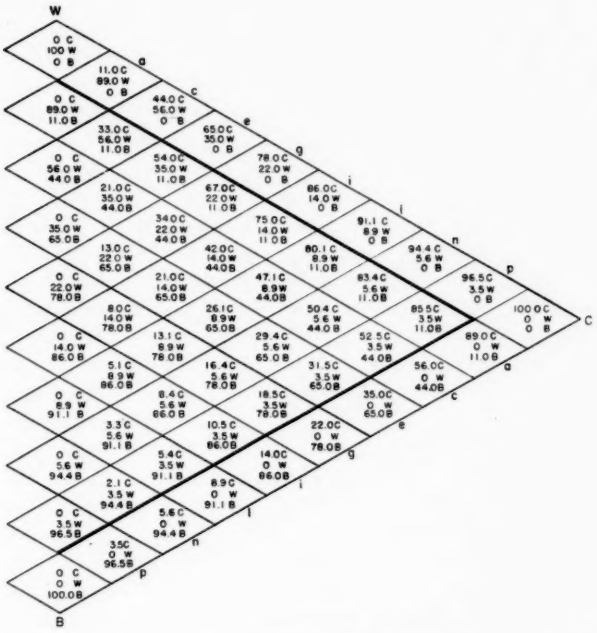

FIG. 3. Proportions of *C*, *W*, *B* for Ostwald's monochromatic triangles.

colorants. If better colorants were obtainable Ostwald would include them.

Before developing a hue scale, Ostwald developed his theory of related and unrelated colors. "Unrelated" colors are those that appear alone in an otherwise darkened visual field; we cannot judge their relation to the source of light; for unrelated colors there is no black, but only white and hue. "Related" colors are the colors of our surroundings, those that we see in relation to the light source; among "related" colors both blacks and grays appear. On the basis of this theory Ostwald called attention to the fact that much trouble in understanding color has been caused because the physicist's measurements are generally of "unrelated colors" while the artist uses "related colors." He stated that black content, white content, and full color are the three elements of every surface color, and adopted these three elements as his "three dimensions" of color.

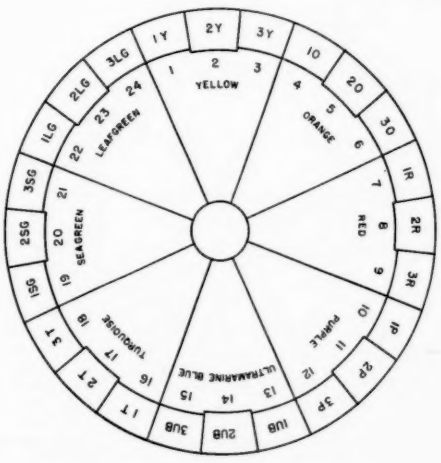

FIG. 4. Ostwald hue circuit, illustrating 24-hue notation. Boundaries are regular since the maximum saturation for each hue is placed always at the same relative position.

These he illustrated on double triangles, the neutrals forming a central axis, white at the top, black at the bottom, with complementary hues at the outer apex of each triangle. How should the colors on the chart be related? Ostwald thought long and hard over this point, and his enthusiasm knew no bounds when he concluded that chromatic color plus black plus white always resulted in unity. This relation accords with the representation of colors of one hue within a triangle, so on the basis of the formula,

$C+B+W=1$, with optical mixture in mind, he devised the proportions shown in Fig. 3 for each of his monochromatic triangles. It will be noted that the proportion from white to full color and from full color to black is the same as from white to black. Absolute white and black were not available, and the colors which he intended to illustrate by his charts are therefore within the solid line. Figures 2, 3, and 4 illustrate Ostwald's method of notation. He used an upper case letter or a numeral to denote the hue, followed by lower case letters to denote white content and black content; for example, *2Rne* or *8ne* indicate the second red (Fig. 4) of the 24-hue scale, or the eighth hue of the 100-hue scale, each having an *n* amount of white and an *e* amount of black.

For the equator of the solid Ostwald developed a series of 100 hues, each color as strong as could be obtained with pigments then available. Again, he states that when stronger colorants are available, they are to be substituted. As a basis for the hue circuit Ostwald used the four primary colors of Hering, with intermediate hues placed between. Beginning with a yellow, these were numbered 1 to 100. Colors opposite were meant to be complementary, as measured by his Polarizing Color Mixer and based on his theory of semichromes. This theory, which can be understood easily in terms of present day spectrophotometry, indicates that ideal pigments should not be perfectly selective, but should reflect over a wave-length range of half of the spectrum. The ideal complementary pigment should then reflect throughout the other half of the spectrum. The division points in the spectrum for the full colors were taken at the wave-lengths of spectral complementaries.

As Ostwald continued to work on the 100-step hue scale* it became clear to him that a scale of fewer steps would have advantages. Therefore the Ostwald Atlas produced in 1920 contained 24 hues with every other step from *a* to *p* in the divisions of the monochromatic triangles. This is the Ostwald system as we know it today and as it is discussed in the only Ostwald color book so far published in English,† his *Farbkunde*, translated as *Colour Science* by J. Scott Taylor, Volume I published in 1931, and Volume II in 1933 by Winsor and Newton Ltd. To accompany these volumes there is a *Colour Album* of Ostwald charts arranged also by J. Scott Taylor and published by Winsor and Newton.

The four Hering primaries, with which Ostwald began his scale, were placed in complementary positions as yellow and ultramarine, red and seagreen. The four intermediates were likewise placed in pairs as orange and turquoise, purple and leaf-green. Each of these eight hues has three variables, one to the right, one to the left, to make a total of 24 hues, Fig. 4.

If the solid is split vertically through the middle, a pair of complementary hues on two monochromatic triangles is seen, Fig. 2. In each monochromatic triangle the outer row of samples (white to full color) is called the light clear series. This, with the remaining rows parallel to it, make up the isotones, each row containing an increasing proportion of black. The lower member of each row is chromatic and the upper is gray. Full-color-to-black is called the dark clear series and, with the rows parallel to it, forms the group called isotints which have a constant white content, increasing from row to row. The lower member in each row of this series is neutral while the upper member is chromatic. The series parallel to the gray scale, each successive series of increased saturation, are called the shadow series, or isochromes. Roman numerals are used to denote these.

Ostwald in his book, *Harmonie der Farben*, lays great stress on these three groups of color relations. Proportional measure of black and white content is the basis of his chief rule for harmony and, of course, proportion is an

* In 1917 and 1918 Ostwald helped in the development of his first Atlas, but before it was completed his eyesight failed and one of his sons completed the work. This gigantic first task resulted in a 100-step hue scale, a 20-step value scale, with triangles completed for steps *a* to *p* for 24 hues, the other 76 hues being limited to fewer steps.

† His *Farbenfibel* was published in Germany in 1916, *Beiträge zur Farblehre* in 1917, *Der FarbAtlas*, with 2500 colors and over 100 charts in 1917. He planned a series of five books on color, published progressively: the *Mathetische Farbenlehre* in 1918, the *Physikalische*, and the *Chemische Farbenlehre* in 1919, *Physiologische* (by Podestu), and the *Psychologische* in 1922. His *Harmonie der Farben* was first published in 1918, then completely reworked in 1920; the *Farbschule, Einfurhrung, Farbkörper*, and *Farbtonleitern* were published in 1919, the *Farbkunde* in 1923. In 1927 Ostwald's 3-volume biography, *Lebenslinien*, was published by Klesig and Company, Berlin. After his death, Ostwald's daughter assembled a 23-page bibliography of his color works.

outstanding principle of all art. For example, he contends that saturated hue is most sparkling when used with black and white; but that a dull color harmonizes with the two grays which contain the proportion of black or white found in the dull color. In his book he suggests how selections may be made for various reduced forms of his color solid.

The Ostwald system has been studied by a number of German and English scientists, and many points are criticized, although on the whole there is a feeling that while it is not the full solution, the system is of great practical value in art education. There seems to have been much application in Germany of the Ostwald system to practical work. Beginning as early as 1920, Kohlrausch, Meissner, Schäffer, Rösch, Klughardt, Richter, Krüger in Germany; Guild, and more recently Eysenck and Parry in the English publication *Nature*, have discussed various phases of the Ostwald work, some have included measurements of his papers. Doctor Guild gives a well-reasoned criticism (March 26, 1932) of the system that should be thoughtfully read by all those who feel that Ostwald gives a complete answer to color. He points out many of the objections that make the Ostwald system of limited use in technical color work. For art work it may not matter that Ostwald's metrical technique gives merely an approximation to *C* and *W* by his methods of filter photometry, but to the technical worker this is extremely important, for it leaves no firm foundation on which to build. Doctor Eysenck takes issue with Doctor Guild on some points for he thinks it is Ostwald's psychological and aesthetic considerations that are of the greatest interest. He reports results of experimental tests made upon four of Ostwald's psychological and color harmony claims. Although his empirical investigations fail to support Ostwald's claims, he says: "In spite of this disappointing conclusion, I believe the main aims which Ostwald hoped to reach are eminently worthwhile, and that a repetition of his work with the proper statistical and experimental safeguards would lead to great progress in those applied arts and sciences which to some degree depend on colour, such as art teaching, poster designing, and camouflage." Doctor Parry's note calls attention to two experiments that he made relating to the aesthetic appeal of Ostwald's chromatic circles, the first with the appeal of single hues, the second with that of triple combinations.* His conclusion is that the complexity of the problem of color harmony is such that any attempt to explain it by a single principle, seems foredoomed to failure.

In our own country a number of colorists have become increasingly familiar with the Ostwald system and translations of several of his books or portions of them have been privately made. In November 1937, *More Business* (American Photo-Engravers Association, Chicago) contained an article by Egbert Jacobson with extensive charts reproduced by color process printing, to describe the Ostwald system. And at the present time Foss, Granville, and Nickerson expect to publish results of spectrophotometric and theoretically developed data which they have obtained. Publication by the Color Laboratories Division of the Container Corporation of America of a new series of working charts is in preparation by Mr. Jacobson, Carl E. Foss having prepared the color chips, which are movable, made on acetate, one side glossy, the other side dull. Publication of these charts will be in two forms, a color harmony index and a series of 13 linen-bound handbooks, each of the first 12 to contain one set of Ostwald complementaries, the thirteenth a text by Mr. Jacobson telling how the charts may be used.

THE MUNSELL SYSTEM

Since a history of the development and scientific application of the Munsell system appeared in the *Journal of the Optical Society of America* in December 1940,[5] it is sufficient to state here that the originator of the system was Albert H. Munsell, artist and art teacher, born in Boston, Massachusetts, in 1858. The story is told that Munsell's need of a color notation came to him most forcibly one evening when he found himself unable to catch quickly enough the changing colors of a particularly beautiful

* A detailed account of these tests is contained in Dr. Parry's Ph.D. Thesis (University College, London, 1940), "The role of attention in aesthetic experience."

[5] Dorothy Nickerson, "History of the Munsell color system and its scientific application," J. Opt. Soc. Am. **30**, 575 (1940).

sunset. Whether or not this is true, by 1901 he had developed the Munsell value scale and a daylight photometer on which to measure it. As an artist, he first painted a scale to suit him; when he measured it, he found that his scale seemed best when made so that the light reflectance of each value chip was the square of the number on his value scale (0 black, to 10 white). This follows roughly the principle of the Fechner law that Ostwald later found necessary

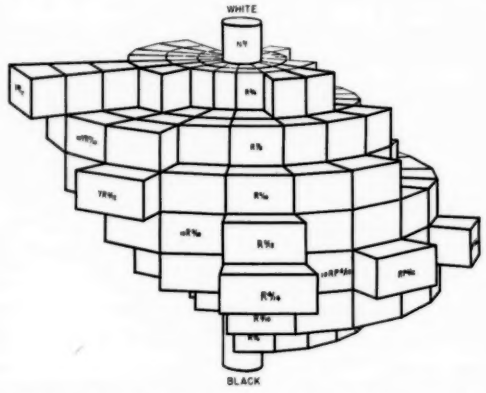

FIG. 5. Munsell solid. This is but one of many ways in which this solid can be illustrated. It can be drawn within a cylinder, or one can use a "color tree," or arrange the vertical "constant-hue" charts, or the horizontal "constant-value" charts so as to get a skeleton arrangement of the solid.

to use if his value scale was to appear equally spaced.

Munsell investigated solids that had been suggested by previous students, the Lambert pyramid, the sphere of Rünge. He liked the idea of the sphere, so he made one, with dark colors at the bottom, light colors at the top, medium colors between. He did not try to place the most saturated colors on the equator, but reduced the saturation (chroma, he called it) of all the stronger colors to match that of the one that had the least saturation at that level (*BG*). He developed a hue circle of five principal hues, with five intermediates placed between them to make 10, for he had decided to use a decimal system, rather than one based on three colors. The five principal hues were determined by selecting colors equally spaced in hue which, when they appeared to have about equal chroma, with value equal as determined by luminosity readings on the photometer, would spin together on a color top in equal proportions to give a neutral gray. Thus he produced a color system based on the three dimensions of hue, value, and chroma, with middle colors that could be illustrated on a sphere. The solid needed to include colors of maximum saturation is of irregular shape, Fig. 5; this irregularity of the solid has to do not only with pigment limitations but also with the fact that the maximum saturations of colors vary from hue to hue and are reached at different value levels. Since each attribute within the solid is presented in measured steps of equally perceptible intervals the outline of the color solid reveals these variations.

Munsell considered the important measurable attributes of a color to be its hue (the quality aspect of color associated with different portions of the spectrum); its value (the degree of lightness or darkness of a color); its chroma (absence of grayness or dullness, or degree of departure from a gray of the same value).

Although Mr. Munsell left little published material, he kept a color diary[2] in which, from 1900 on, he kept careful note of details having to do with the development of his system and its application to teaching and to commercial work. Although there has been a great deal of use and application of the Munsell system to commercial and scientific work in recent years, Mr. Munsell was more interested in applications to teaching than to any other phase of his work. He believed that proper color training should begin with children, and spent much time in writing outlines for primary school grades and in conferences with art teachers and supervisors. He felt that if children were properly taught, color would have more meaning and use for them all through life, and this became more important to him than ever when the early phases of development of his system were completed.

In 1920 the National Bureau of Standards published Technologic Paper No. 167, "An examination of the Munsell system," in which it stated that "a revised edition of the *Atlas* and *A Color Notation*, based upon the best present day methods of measurement and specification, would be a most important contribution to the science and art of chromatics generally." Five proposals were made: standardization should be

made of the value scale; each color should be specified in terms of physical measurement; colorimetric and photometric specifications should accompany the *Atlas*; value measurements should be made with reference to a standard white; and general agreement in the nomenclature should be obtained before issuing a revised publication. Although Mr. Munsell died before this report was completed, the company established to handle the early sale of charts and school supplies continued the work through the establishment of the Munsell Research Laboratory in line with the Bureau of Standards proposals, with the result that in 1929 a revised edition of the *Atlas* was published, called the *Munsell Book of Color* to distinguish it from the original *Atlas*. As far as teaching goes, the color chips on the *Atlas* charts are not very different from those of the *Book of Color*, except that the 1929 edition of the *Book of Color* contains 20 instead of 10 hues, and the colors are based on a revised value scale that gives visual steps more nearly equal than those of the early square-root scale.

The Munsell hue circuit begins with five principal hues, red, yellow, green, blue, purple, to which the five intermediates yellow-red, green-yellow, blue-green, purple-blue, red-purple are added. These are called the ten *major hues*. For greater variety and discrimination (necessary in color measurement work) a scale of 100 hues may be used. In this case there will be 10 hue steps in the red range, 1st *R*, 2nd *R*, etc. to 10*R*, the 5*R* being the principal hue. Value-chroma charts in twenty constant hues have been available since 1929, but the number has recently been increased to forty. Figure 6 shows the complementary arrangement of the ten major hues. Figure 7 shows the notation for hue in three forms, one in letters of intermediates, one simplified in terms of 10 hues, and one in terms of 100 hues by numbers. Because many teachers prefer to use names instead of numbers, the hue notation is provided with names (capital letters for noun forms, lower case letters for adjective forms, as *P* for purple, *p* for purplish), but the use of numbers with letters for 10 hues is recommended as better practice. The use of numbers only is usually confined to laboratory practice.

Munsell thought the concept of value an important color attribute, and his charts show constant values on a single horizontal plane. Pigments having saturated hues often differ from each other in their values, for example, the pigment having the most saturated yellow has a value not much less than that of white while the pigment having the most saturated color in the complementary purple-blue, is in value near to black. This, and the fact that the full saturation of one hue is not always as great as that of another, is the reason for the variation in the form of the Ostwald and Munsell solids, Figs. 1 and 5. Compare also Figs. 2 and 8, 4 and 9.

Among teachers, criticisms are sometimes heard of the Munsell "middle" colors, or of the Munsell sphere on which there are displayed colors of a saturation equal to that of the maximum blue-green. Such criticism is based on a misconception of the "middle" colors, and of

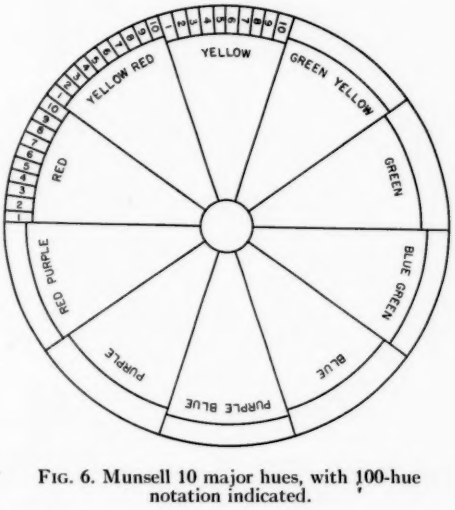

FIG. 6. Munsell 10 major hues, with 100-hue notation indicated.

the sphere. No one is limited by the colors on the sphere, for it is but a portion of the color solid. But the "middle" colors are basic to the establishment of the Munsell system, for they are colors of constant value and chroma, and only when these two attributes are constant can the third attribute, hue, be studied in terms of "equal steps." In Munsell's day colorants provided a permanent red that was about /10 in chroma, but colorants that produced a

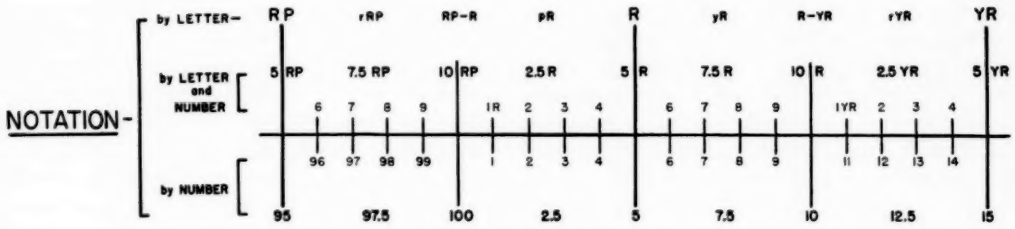

FIG. 7. Munsell hue notation, showing relation of names, symbols, and numbers.

reasonably permanent blue-green were only half that, or /5. Therefore it was the blue-green that limited the original Munsell sphere to chromas of /5. A *complete* solid would contain all possible colors, and would be irregular in shape; the sphere is but a portion of the complete solid.

The value-chroma relations of each Munsell hue can be graphically shown on a constant hue chart and the hue-chroma relations can likewise be shown on a constant value plane; but whereas Ostwald shows all his colors on triangles similar in size and shape, or on complete circles, many of Munsell's charts are dissimilar both in shape and size, Figs. 2 and 8, 4 and 9. The advantage in the Munsell concept is that the notation of colors does not need to be disturbed when new colorants make it possible to produce chips for colors not now represented on Munsell charts. As fast as new colorants will produce chips of permanent color, such chips can be added to extend the Munsell charts. The shape of the present charts is limited by permanent colorants obtainable today. The reds and yellows extend far out toward the limit of possible colors but the greens, blues, and purples obtainable by colorants available today are not near the limits, for even impermanent dyes and pigments in those hues do not approach the limit of colors of "maximum visual efficiency."* Figure 8 illustrates the present boundaries of two typical vertical planes, and Fig. 9 those of the middle horizontal plane in the Munsell solid.

The notation of the Munsell system is so simple, yet has possibilities of such accuracy, that the system has become increasingly important during the past 25 years in industrial, commercial, and scientific work as well as in art education. The notation consists of the symbols for hue, value, and chroma, written in that order, the letter (or numerals) for hue written first, then the numerals for value and chroma written as a fraction, thus, *H V/C*; for example, a red, four in value, ten in chroma, is written *R* 4/10, and is read, "Red, four, ten." This does not mean four-tenths. The fraction sign is used as a convenient symbol only; it does not indicate a fraction. For technical work it is possible to subdivide the steps of hue, value, and chroma still further, but in most art expression this is not necessary.

For a dramatic visualization of the color solid concept the teacher may present it as a sort of modern World's Fair building in the form of a cylinder. Its central core is an elevator shaft entered in utter blackness in the sub-basement. If you ride in the elevator you proceed from this blackness by degrees to utter whiteness at the top. At each floor level the elevator takes on the appearance of a lighter gray. On each floor corridors radiate from this central elevator toward the outside of the building. As you leave the elevator at, say the fifth floor, you notice that all the colors are of value 5/, neither very light nor very dark. Perhaps you start down the red corridor. Near the elevator shaft all the red colors appear dull. As you proceed away from this central area the impression of redness increases until at the end of the corridor it is vivid! You could observe like effects in the green, blue, or purple corridors, or on other floors.

If you stand in the central shaft and turn about, as on a pivot, you may scan each hue in the circle about you, red, yellow, green, blue, purple, just as you might scan the horizon. It may be easy for students to remember the

* See D. L. MacAdam, "Maximum visual efficiency of colored materials," J. Opt. Soc. Am. **25**, 361 (1935); and "Theory of the maximum visual efficiency of colored materials," J. Opt. Soc. Am. **25**, 249 (1935).

invariable arrangement in the color solid if they remember that *H* stands for hue, and also *horizon*. Dull hues form a near horizon as on a dull day, vivid hues a far horizon as on a clear day. The lower floors are dark in color, the upper light; therefore they might remember that *V* stands for value, also for *vertical*. Near the central shaft all is dull and gray; farther out all becomes more intense and vivid. The symbol *C* stands for chroma, also for *centrifugal*, radiating horizontally away from the neutral pole.

Munsell did not give many rules of color harmony. He did suggest that all color combinations that spin to gray should be harmonious, and he thought that children should begin with middle colors instead of colors of maximum chroma. While both of these suggestions produce good results in some cases, good results do not always follow.* Yet there are many ways in which the selection of color harmonies may be made by use of the Munsell system. Some artists are enthusiastic about the new and interesting color combinations found by selecting various types of orderly paths through the color solid. The possibilities are so numerous that one never need fall into the rut of commonplace selection. The broadening of the world of color possibilities is one of the best contributions of the Munsell solid; the charts of the Munsell system are merely skeleton maps of this color world.

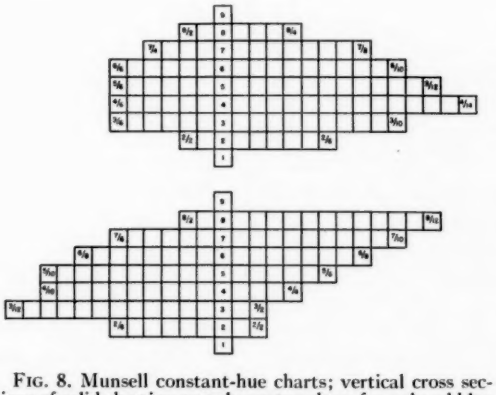

FIG. 8. Munsell constant-hue charts; vertical cross sections of solid showing complementary hues for red and blue green; yellow and purple blue. Boundaries are irregular because intervals between colors are equal in value and chroma.

* See criticism by Faber Birren in July 1941, *Inter-Society Color Council News Letter*.

Because of the general usefulness of the Munsell concept of hue, value, and chroma, the Munsell system has been increasingly applied in this country to practical and technical color work. That in turn has led to scientific investigations. At various times since 1912 the National Bureau of Standards has examined the Munsell system. Since 1937 the Newhall subcommittee of the O.S.A. Colorimetry Committee has been at work studying the spacing of the

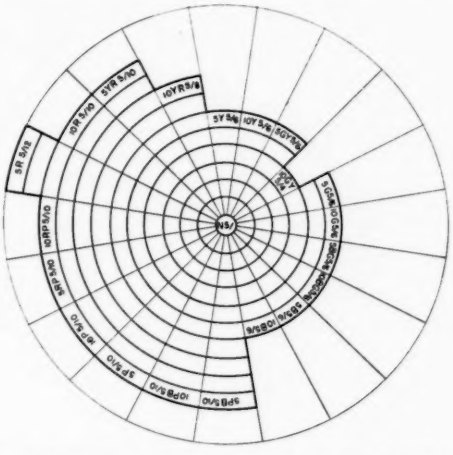

FIG. 9. Munsell constant-value chart; horizontal cross section of solid at 5/. Boundaries are irregular because equal chromas are placed equally distant from the neutral core of the solid.

Munsell colors with the purpose of preparing a set of smoothed contour diagrams to represent an ideal Munsell system. In 1938 the Agricultural Marketing Service‡ (USDA) published a preliminary report that included tentative smoothed chroma contours. In December, 1940 a series of five papers on the Munsell system appeared in the *Journal of the Optical Society of America*, including Glenn-Killian data for I.C.I. Illuminant *C*, based on spectrophotometric measurements for the papers of 20 hue charts of the *Book of Color*. Similar spectrophotometric measurements have since been made at the National Bureau of Standards and the colorimetric data will be published soon by Gibson and Kelly. Using the Gibson-Kelly spectrophotometric data for these colors, the Agri-

‡ Now a part of the Agricultural Marketing Administration.

cultural Marketing Administration (USDA) has computed results for three other illuminants: I.C.I. Illuminant *A* (tungsten), Macbeth 7500°K (moderately overcast north sky), and clear sky. Based on these results, information for other phases of daylight can be interpolated. In the spring of 1942 the Munsell company completed papers for another set of 20 intermediate hue charts, making a total of 40 hue charts now available. As fast as the colors for these additional charts have become available they have been measured spectrophotometrically and the colorimetric data made available informally by Granville, Nickerson, and Foss; a complete report will soon be ready for publication.

Recently the Munsell notation was included as a means of color specification in a War Standard of the American Standards Association. According to this standard, the basic specification of color will be in terms of the internationally adopted I.C.I. method described in the previous paper by Dohner and Foss. For the popular identification of color the standard recommends the Munsell color notation. When names, and not notations, are required the standard recommends the ISCC–NBS system of names,[6,7] and since the boundaries of these names are expressed in Munsell notation, it is necessary to use or understand the Munsell notation for all but basic technical work. Even in technical work the Munsell notation is very often used, for it has the great advantage that it can be understood and related to the color experience of that group of practical people, untrained in colorimetry, for whom technical color studies are often conducted.*

At the present time practically all the proposals made by the National Bureau of Standards in 1920 concerning the Munsell system have been carried out. Thus, with the scientific data now available, or soon to become available, there seems to be sufficient information to provide a sound basis for its use in many fields besides the art-education field for which it was first developed.

COMPARISON AND COMMENT

For color specification, the Munsell system is more useful than the Ostwald, and for this there are several reasons. First, the three-dimensional concept of Munsell hue, value, and chroma is identifiable with the psychological and psychophysical concepts used in colorimetry,‡ while the three-dimensional concept of Ostwald's full color, black content, and white content is not. Because the scales of Munsell value and chroma are the same for all hues, it is easy to learn to identify colors in the Munsell notation even without the presence of charts. This is not easy in the Ostwald notation, since colors with similar black and white contents may appear very unlike. Second, the end points of the Ostwald charts are not fixed points. (If they were fixed at ideal full color, there would be many spaces on the charts that could not be filled in.) Third, there is no Ostwald notation for many colors that can be produced outside of the Ostwald triangles by the same colorants that produce the end points of those triangles. Conversely, many spaces on the triangles require the use of colorants that differ considerably from those used to produce the *pa* colors of the Ostwald charts, and this would still be true if ideal colors were used as fixed end points. Fourth, there are many colorants whose colors fail to receive an Ostwald notation because they lie outside of the monochromatic triangles and again, this would be true even if ideal colors were used as fixed end points.

On the other hand, many teachers have found that they can use the Ostwald system more successfully than Munsell in teaching color harmony. Certainly it is easy to follow the many straight and curved line paths through the Ostwald solid, and to make color selections from those paths. Ostwald has made so many suggestions for selecting color harmonies that

[6] Deane B. Judd and Kenneth L. Kelly, "Method of designating colors (ISCC-NBS Method)," J. Research Nat. Bur. Stand. **23**, 355–385 (1939).

[7] Dorothy Nickerson and Sidney M. Newhall, "Central notations for ISCC-NBS color names," J. Opt. Soc. Am. **31**, 587 (1941).

* Just prior to the Inter-Society Color Council meeting at which this paper was presented, the formation of a Munsell Color Foundation was proposed by the Munsell Color Company, with special trustees to be appointed by the National Bureau of Standards and the Inter-Society Color Council, the policies of the company to be decided by the Foundation trustees "in the best interests of color in science, art, and industry." This Foundation is now in the final stage of organization.

‡ The concepts referred to are: psychological hue, lightness, and saturation; psychophysical dominant wavelength, luminous reflectance, and purity.

teachers find studies of his work stimulating, particularly studies involving the isotint and isotone series. Others have done the same thing for the Munsell solid, but little has been published; there are quite as many paths through the Munsell solid as through the Ostwald, and all the ideas suggested by varying paths through the Ostwald solid can be adopted for use with the Munsell, although not always with equal convenience.

One thing that the authors of this paper would like to leave with their readers, particularly with their art teacher readers, is that rules or guides to color harmony are a thing apart, even if developed by Ostwald or Munsell. Each could have developed his concept of ordered color relations and could have illustrated it with charts without saying a single word about color harmony. The converse is not true; for any rules or guides that relate to color harmony must be based on some concept of an orderly arrangement of colors. By illustrating their concepts with carefully prepared color charts, both Ostwald and Munsell have succeeded in bringing ordered relations of color into clear view; they have given us systems of color order, of color worlds for which their charts provide us with maps. It is the concept of each system that is important; its use may be varied and individual!

Results of a Questionnaire on Color in Art Education

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(Received August 17, 1942)

THIS paper is based upon returns from a questionnaire sent to about 150 persons engaged in teaching students of art on the higher education level. A series of questions was prepared to cover two topics on this program, i.e., "What color facts shall be taught to art students?" and "What technical information and materials are desirable for color study?"

Replies were received from 35 persons, representing 16 states, 17 colleges and universities, and 9 art schools unaffiliated with such institutions, one color specialist and two designers. The teaching profession was represented as follows:

Art in General:	8	Advertising Design	1
		Costume Design	1
Art Education:	3	Design	5
		Home Economics (Art)	1
Special Subjects:	21	Industrial Design	2
		Mural Design	1
Psychology:	1	Painting	9
		Theater Design	1

The list of institutions filing returns is as follows:

Alabama College
University of Alabama
University of Cincinnati
Columbia, Teachers College
University of Connecticut
Milwaukee State Teachers College
University of Nebraska
University of New Mexico
New York University
Oregon State College
University of Oregon, School of Arch. and Allied Arts
Peabody College
Stephens College
Newcomb College, Tulane University
Wellesley College
Western Reserve University
Carnegie Tech., Pittsburgh
University High School
Boston Museum of Fine Arts School
Cleveland School of Art
Massachusetts School of Art
Newcomb Art School, Tulane University
Norwich Art School
Pratt Institute
Rhode Island School of Design
Taos School of Art, New Mexico
Worcester Art Museum School

Any questionnaire is a dangerous and forbidding instrument. Do what you will, it is as distasteful as an income tax form, and with everyone whom you entice into answering, if completed at all, the results are often indefinite and conditional. Therefore, although the findings in this paper are merely signs or indications of color teaching trends, they suggest points of view and may be likened to "token flares" rather than "explosive bombs."

"WHAT COLOR FACTS SHALL BE TAUGHT TO ART STUDENTS?"

This topic was divided into four sections as follows: (A) "What should be the initial approach to color study?" (B) "Following the initial steps in what order would you present other phases, if any?" (C) "Would you have students study color theories?" and (D) "Would you base your final productive student work in color on one of these theories?"

Under (A) "What should be the initial approach?" four suggestive approaches were offered under the terms "creative," "scientific," "psychological," and "historical." The person answering might choose others if he so desired. Of the 35 returns 21, or 60 percent, indicated "creative" as their initial approach.

Whether its position as first in the list influenced this selection of "creative" as the first approach is open to question. I believe, that in contrast to the other three terms this choice was wholly intentional. At once the question is raised in one's mind. "What is meant by creative?" So many agreeing on this word leads me to believe that there is some unanimity of understanding, though there probably is considerable divergence as to teaching methods. I venture to state that in the minds of these 21 people the term creative means free experimentation, unrestricted manipulation as a first step in actually playing with color, individual analysis and discovery unhampered by rules, principles, and previously discovered encumbrances which tend to frustrate curiosity and initiative in a beginner.

The remainder of the 35 questionnaires indicated for first steps different individual ap-

[1] Executive Vice President, Rhode Island School of Design.

proaches or combinations of approaches as follows:

Scientific:	2, Universities
Psychological:	3, 1 University, 1 College, 1 Art School
Historical:	1, An independent specialist
Creative and Scientific:	3, 1 University High School, 2 Mfgr. designers
Creative and Psychological:	2, 1 Technological Inst., 1 Art School
Scientific and Psychological:	1, University
Creative, Scientific, Psychological:	2, Art Schools
Creative, Scientific, Psychological, Historical:	1, University

"and others depending on purpose."

As a second step in the approach to color, no one checked "creative," 5 indicated "scientific," and 3 "psychological." Two checked "scientific" for a third step, 5 reported "psychological," and 2 "historical." Five indicated "historical" as a fourth step. However, other approaches were indicated and included the following:

1—sources of material (earths, commercial, synthetic)
1—structural
3—physiological
1—objective study
1—technical research
1—study of eye function
1—step by step system of color relationship.

It would appear, therefore, that on the basis of these returns the approaches to the study of color for art students are, in the order of listing in the questionnaire, i.e., creative, scientific, psychological, and historical.

Under the second division of the main topic, (B), "In what order would you present other phases?" the findings under division (A) were verified. The following is an analysis of answers to this question:

Colleges and Universities

Scientific	*Psychological*	*Historical*	*Creative*	*Structural*
6—first	5—first	1—first	1—first	
3—second	4—second	2—second	2—second	
1—third	1—fourth	2—third	1—third	
		1—fifth		
		1—as needed		

Schools of Art

Scientific	*Psychological*	*Historical*	*Creative*	*Physiological*	*Textile Research*
4—first	2—first	1—first	1—first	1—first	1—fifth
1—second	1—second	1—second		1—second	
1—third		1—third			
1—fifth		1—fourth			
		1—fifth			

Color Science Institute, New York

Psycho-physiological aspects; chemical problems; advanced system of color relationships as applied to surface color.

Under division (C), "Would you have your students study color theories?" the replies were largely in favor of so doing. Twenty-seven voting "Yes" represented 15 from Colleges and Universities and 12 from Schools of Art. Six others also approved. Two, only, replied "No;" yet one of these reported, "But if student feels it urgent, would recommend Ross."

Under the second half of division (C) question, i.e., "If color theories, what ones?" 16 representatives of colleges and universities mentioned theories as follows: Munsell, 13 times; Ross, 6; Helmholtz and Ostwald, 5 each; Chevreul, 3; Hering, 2. Fourteen representatives of schools of art mentioned Munsell and Ross with 9 each, Ostwald 8, Chevreul 4, Helmholtz and Hering 3 each, and two theories not listed in the questionnaire—Ladd-Franklin and Dudeen. Among the remaining returns Munsell was mentioned 4 times; Ostwald twice; and Birren, Ladd-Franklin, Hering, and Goethe, 1 each.

The following comments from representatives

of some of the different institutions are significant:

University of Alabama: "A background of many theories should be given so that no one would be given as 'the truth.'"

Columbia, Teachers College: "Theories supplementary to creative color experience only."

New York University: "Color relations or systems—but not so-called 'laws of harmony'—what is available is untrue, limiting—Munsell, yes; Helmholtz, no; Hering, no."

Oregon State College: "Yes, for industrial students."

Wellesley College: "Yes, for light mixtures."

Western Reserve: "Here, you should differentiate between theories of color vision, i.e., Helmholtz, Hering; theories of color standardization, i.e., Munsell, Ross; and theories of color combinations, i.e., Chevreul, Ostwald. The last two categories are most important to the student."

Boston School of Museum of Fine Arts: "Munsell. Others by lectures and reading."

Newcomb Art School, Tulane: "The more one knows about his subject, the better."

Norwich Art School: "Ross and Munsell for first-year groups, followed by Ostwald and Chevreul. Other color theories are touched upon."

Pratt Institute: "They must get a color concept."

Rhode Island School of Design (Painter): "Dudeen color triangle (Chas. A. Winter) further adapted to practical use on painting by John Sloan (Gist of Art)."

Taos School of Art: "Lectures on most of them, preferably Ross and Ostwald."

Worcester Art Museum School: "Ostwald, and composite simplified system."

Division (D) also deals with theories and the question reads, "Would you base your final productive student work in color on one of the so-called theories?" Seventeen replied "No," 4 "Yes," and 15 answered "In part only." Seven mentioned Munsell for partial use, 2 specified Ostwald, 2 Ross, and one stated, "Unfortunately, my own, which attempts to make use of the best standardization and combining."

Divisions (E) to (L) in the questionnaire deal with different phases of color study as follows: creative, physical, chemical, psychological, physiological, historical, philosophical, and any others the persons answering might suggest.

Under each phase the answer was to indicate (1) the specific mode of study for the topic; (2) the means provided for practice and research in the field covered; and (3) the percentage of time in color study devoted to it in each year of the four.

For example, one reply gave the following for "Creative" work:

(1) The method or study type is through "Design."

(2) The means employed is "colored chalk on colored paper and cut paper."

(3) The time for this part of color study is "50 percent the first year and 50 percent the second."

Had all of this series or any one section of them received answers as direct and simple as this one the results would be of considerable interest, and of real value. It was apparent, however, that these questions either were unintelligible or they gave rise to personal points of view which were stated from standpoints of school curricula or professional interests.

There were 32 out of the 35 who answered one or more of the questions designated. In some cases there were no specific written replies but merely check marks to indicate that one or more of these seven approaches was employed.

A sample of different replies, however, may be of interest:

(E) *Creative Work (30 answers)*	*Topic*	*Method*	*Time*
Processes of origination, invention, experimentation	Create color composition 1. Color that regresses in distance 2. Color that is flat 3. Color that leads to center of attention "And so on for 500 problems."	Specific assignments "not that a student should ever be permitted to just paint." Theatrical design	50 percent each year

(F) *Physics (19 answers)*			
The science of light, color	Color mixture Mobile color design "Color organ"	Color organ project A recital	10 percent each year
(G) *Chemistry (18 answers)*			
Chemical intermixture of color vehicles	Color scales and problems	Water colors, gouache dyes, dyeing problems	20–30 percent 2nd year
(H) *Psychology (29 answers)*			
Mental emotional reactions, instincts, phenomena	Association, contrast, mood induction by color	Jung (Free association) Wells (Effective value technic for classifying, energizing, tranquilizing and subduing colors) Lecture and practice Designing by induced moods through musical recording	
(I) *Physiology (18 answers)*	*Topic*	*Method*	*Time*
(Structure, function, and processes involved in seeing)	Rod-cone reception, afterimage, thresholds, light and dark adapted vision	Lecture demonstration and practice making hue, value and chroma scales based on visual perception and discrimination	5–6 percent 1st year
(J) *History (23 answers)*			
(Chronological data of past men, times, places)	History of art	Museum research	10 percent 1st 3 years 5 percent 4th year
(K) *Philosophy (22 answers)*			
(Causes, theory, reason systems, ideology)	Part of all required courses in appreciation	Lectures, demonstrations, laboratory work	10 percent, 3rd year 25 percent, 4th year

Other classifications included Function, Techniques, Practical work such as a shop or business, and Textures. Only one complete answer was given under these classifications. That was under Function, and is as follows:

(L) *Function*	*Topic*	*Method*	*Time*
	Color in painting Daily painting class	Expressive use of color values related to form	50 percent, 1st and 2nd years 75 percent, 3rd and 4th years

The final question (M) in this group under "What color facts shall be taught?" is "Would you use, for example, the approach to and the same method of teaching color in Fine Arts for students in all other art courses?" Thirty-two out of 35 filed some answer, and of these 20, or 62.5 percent, answered "Yes," 7 replied definitely "No." There were few comments on this question, perhaps seven or eight, but this one speaks for the rest, "The approach depends largely upon the mentality of the student and upon the ability of the instructor to make the connection for a specialized point of view."

Perhaps the 35 returns are a fair representation of a cross section of schools and colleges throughout the country and yet one could wish for the judgments of professors and teachers of from at least two dozen more institutions where strong professional art courses are being given.

It is apparent that the present trend in color teaching for prospective artists and designers is through the creative approach, with the schools of art showing a slightly higher percentage in its favor than the colleges and universities. Returns further show that other phases of study are in the following order: scientific, psychological, and historical.

On the question of color theories 92 percent were in favor of having some theory in the course. Munsell appeared to be in the lead but many teachers would present other theories as well. It is interesting to note, however, that while theories are deemed educationally valuable final production is felt to be less dependent upon one theory than upon partial theoretical applications plus the results of the other approaches such as creative and psychological.

It is evident also that combinations of approaches are common in both colleges and schools of art. There is great variation, however. While the creative approach predominates many combine with it one or more of the others.

On the means employed in teaching color no less than eleven different ways were listed: 22 use the laboratory or experimentation method, 12 list lectures, 11 the library, 10 demonstrations. The others referred to are museum research, field research, discussion, thesis notes, reproductions, seminar notes, and observation. Combinations also are stated, preference being for the following: lecture and laboratory; lecture, laboratory, and demonstration; and lecture, laboratory, and library.

"WHAT TECHNICAL INFORMATION AND MATERIALS ARE NEEDED FOR COLOR STUDY?"

The second major question asked what technical information and materials, equipment, and publications were desired for color study. Under materials, returns are as follows: water color paints, 30; colored papers, 27; oils, 24; fabrics, 21; powdered colors, 20; colored chalks, 18; and wax crayons and colored pencils, 15. Other materials used are dyes, gelatins, inks, temperas, glazes, yarns, plastics, wall papers, carpets, paintings, colored advertisements, colored lights, and chemicals. The wide range of materials listed readily indicates the possibilities for color manipulation and demonstration.

Under equipment, we have the following results: color slides, 24 returns; color-mixing motor, 18; color light mixer, 18; colored glass, 15; photometer, 12; cameras, 12; spectroscope, 11; and 13 have special rooms which are used for color study. Among other pieces of equipment are mentioned illustrated charts, colored fabrics, ink and rolling equipment, charts of textures, color solid, Munsell color wheel, Munsell atlas, Allcolor cabinet, and "scratchbooks."

The third part of this question had to do with publications, that is, "List of titles, authors, publishers, and dates of the fewest number of books indispensable to art students." Thirteen out of 35 think that no book is indispensable. The following reply needs no elaboration: "I wish I knew of one. I have a bookcase full on which I won't pay trucking."

Others, however, listed books which they feel are valuable, although in most cases publishers and dates were absent. In some instances references were made to chapters only, while others specified books for specific uses. "There exists no very *complete* or good book. One must cull from several," writes one person; and another says, "The comments by Cezanne on functional color are valuable." A third writes, "No magazines; all are too 'arty' for our use."

Following is a list of authors with the number of times they were mentioned:

Birren, Faber:
"Color Dimensions" (3 times)
"History of Color"
"Monument to Color"
"Functional Color" (2 times)
"Story of Color"
Carpenter: "Colour"
Carrington, Marie Sweet: "Color for Everyone," an introduction to and series of exercises adapted from the Ostwald Series
Chevreul, M. E.: "Study of Color"
Clark
Cleland's "Interpretation of the Munsell System"
Doerner, Max: "Materials of the Artist"
Faulkner, Ray: "Art Today"
Field, George: "Analogy of Color"
Goldstein, Harriet: "Art in Everyday Life" (2 times)
Graves, Maitland: "Art of Color and Design" (6 times)
International Printing Ink Company:
"Three Monographs on Color"—
"Color as Light"
"Color as Chemistry"
"Color in Use"
Jacobs, Michel: "The Study of Color"
Luckiesh: "Language of Color" (2 times); "Color and Its Application"
Mayer, Ralph: "The Artist's Handbook of Materials and Techniques"
Burris-Meyer: "Color and Design in the Decorative Arts"
Moholy-Nagy: "The New Vision"—color chapter
Maerz and Paul: "Color Monograph"—"Color Dictionary"
Munsell: "Color Notation" (9 times); "Book of Color" (4 times); "Munsell Atlas"; "Student Color Charts"
Ostwald, Wilhelm: "Color Science," translated by J. Scott Taylor (4 times) "New Ostwald Charts" (2 times)
Pope, Arthur: "An Introduction to the Language of Drawing and Painting" Vol. I—"The Painter's Terms"
Rood: "Color for Painting"
Ross: "A Theory of Pure Design" (2 times)
Sargent, Walter: "The Enjoyment and Use of Color" (4 times)
Sloan, John: "Gist of Art"
Teague, Walter: "Design This Day" (2 times)
Van Doren: "Industrial Design"—chapters on color
Weinberg: "Color in Everyday Life" (3 times)
Vollard: "Conversations with Cezanne"
Magazines:
"More Business"—"Technical Studies"—"The Colorist" "Vogue"—"Harper's Bazaar"—"The Inter-Society Color Council News Letter"—Fashion magazines, if they are good.

It is a little surprising that no single medium is recommended for use by all persons replying to this questionnaire. One might have supposed that water color would have been found indispensable in the teaching of color to art students by everyone, yet five persons failed to report it. Of the total 35, 27 use colored papers, yet only 15 check crayons or colored pencils, which are inexpensive media and easily obtained.

It is noticeable also that barely half the number replying use color equipment other than slides, and only 24 of the 35 use those. Color is fundamental in any artist's or designer's education but here one finds that comparatively little use, apparently, is made of the technical facilities at hand to aid in teaching.

No science professor would think that he could depend upon formulas, chemicals, and books alone; of necessity he must use various kinds of physical apparatus to study scientific phenomenon. The art professor has a similar opportunity, but only 50 percent in this group seem to grasp their import and use them.

On the matter of books there is a wide range listed, with the authors Munsell, Graves, and Ostwald in the lead. But color study for art students is not a matter of reading one or two publications; rather, it is a combination of activities, experimentation, manipulation, and observation, as well as reading, and because of numerous approaches, writings from practical as well as the theoretical points of view are important.

CONCLUSIONS

There appears to be no great uniformity in the teaching of color to prospective designers and

artists. Most teachers tend to approach the subject creatively for a first step, with psychological and scientific study as correlative means toward the desired end. Occupational objectives on the basis of which these teaching facts and techniques might have been obtained did not form a background for this study. Therefore the returns quite naturally were subject to varying conditions imposed locally by the exigencies of each situation. Naturally the teacher-painter no doubt considered the questions wholly in the light of his own professional interest, likewise the teacher-designer, and the practical designer employed in industry. The painter's basic knowledge of color, consequently, would be developed to emphasize relationships for idealized pictorial applications which would vary markedly from the more restricted industrial designer's reactions, attention values, and related color needs.

While the questionnaire brought out many interesting facts and indicates a limited interest in a scientific approach, which probably accounts for the small utilization of color apparatus, there was no single target set up at which to shoot. Each one therefore aimed from a different angle at his own bull's eye. Probably few teachers of art students are really competent to determine fundamental color facts or essential prerequisites which are basic to all the numerous art professions. Their own special fields wherein color is often supported only by empirical knowledge tend to limit their thinking and tinge their beliefs. Perhaps no one has addressed himself specifically to this task.

The returns also impress one with the feeling that color study is chiefly incidental to student technical practice. This is borne out by the limited amount of time devoted exclusively to it in an advanced 4-year program of art education. For most of us the sense of sight is the most important one and as Ostwald points out: "The sensations we meet with as elements of all vision are colors, and nothing *but* colors." An ordered understanding of this common phenomenon, therefore, seems sensible in any art student's course. Thus Munsell bases his practical scheme of notation upon this basic idea with his system of visual thinking. He combines his experiences as a painter and his physical studies as a scientist in a plan to achieve an ordered foundation of color knowledge. Others have sought to do the same thing with varying results but few, if any, authors have successfully brought this scientific approach into line, as a fundamental step, with the purely aesthetic considerations of the painter and the utilitarian practices of the creative designer—certainly not to the point of general acceptance by the art teacher. And probably this will not be accomplished until more time is given to the study of color in our art courses for professional art education and in connection therewith to a careful consideration of common principles underlying color relations which can be universally accepted as the foundation for advanced procedures and applications.

Such a meeting as has been held here today indicates that much of the information we need is already available, or could be made available if only the technical people and the art education people can succeed in getting together to put the material into a common language. It marks a beginning that we hope will finally develop into a satisfactory answer to the art educator for the facts and materials that he needs in teaching color.

Calculation of the Color of Pigmented Plastics*

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(Received July 25, 1942)

1. INTRODUCTION

A NUMBER of papers dealing with the colors of pigments suspended in some transparent medium have appeared from time to time in the literature.[1] While the theoretical treatment has in general been similar in a number of these papers, the theory has not been put into a particularly convenient form for use, and, for the most part, the experimental results have not been very convincing. An exception to this is the recent paper by Duntley,[1] in which a complete theory of the transmittance and reflectance of a pigmented medium is given. Duntley's theory in its general form employs six constants, and in this form is rather complicated for routine use. The experimental technique described for the determination of the constants is also not very convenient.

While Duntley's theory is necessary for the treatment of translucent samples, considerable simplification can be made for treating the opaque case. In this paper the usefulness of the two-constant theory for the calculation of the color of opaque pigmented materials is demonstrated. Convenient methods suitable for routine use for determining the optical constants of dyes and pigments are described, and the calculations of the color of mixtures of pigments and dyes are illustrated by means of spectrophotometric curves. The method has been used with considerable success by the author for making calculations on the color of pigmented plastics. After a catalog of dyes and pigments has been built up, it is possible to calculate the mixture required to achieve a desired color. The method is therefore useful in color matching, and for general trouble-shooting in color work.

2. GENERAL THEORY

In the two-constant theory, it is assumed that the optical properties of a pigment can be described by two constants, μ and ρ, which may be called the absorption and scattering coefficients. In general, for any pigment, both μ and ρ are functions of the wave-length of light λ. The constants μ and ρ are defined such that the decrease in intensity $-dI$ of light due to absorption in passing through a thickness of medium dt is $I\mu dt$, and that due to scattering in the same thickness is $I\rho dt$. These assumptions lead directly to the differential equations given by Kubelka and Munk[2] in a paper concerned with the opacity of translucent materials. The solutions may be expressed as

$$T=\frac{2ae^{-at}}{\mu+\rho+a-(\mu+\rho-a)e^{-2at}}, \tag{1}$$

$$R=\frac{\rho(1-e^{-2at})}{\mu+\rho+a-(\mu+\rho-a)e^{-2at}}, \tag{2}$$

in which T is the transmittance, R the reflectance, t the thickness of the sample, and

$$a=(\mu^2+2\mu\rho)^{\frac{1}{2}}.$$

The above equations have been given by Amy[3] and others. If the coloring material has only an absorption coefficient, as in the case of dyes, then $\rho=0$ and Eq. (1) reduces to $T=\exp(-\mu t)$, which is Beer's law, and Eq. (2) becomes $R=0$. If the colored medium is thick enough to be opaque, the equations become[4]

$$T=0,$$

$$R=\frac{\rho}{\mu+\rho+a}=\frac{1}{\frac{\mu}{\rho}+1+\left[\frac{\mu}{\rho}\left(\frac{\mu}{\rho}+2\right)\right]^{\frac{1}{2}}}. \tag{3}$$

* Presented at the Summer Meeting of the Optical Society of America, held at the Massachusetts Institute of Technology, Cambridge, Massachusetts, July 21–22, 1942.

[1] For a good summary of the previous literature and list of references, the reader is referred to S. Q. Duntley, J. Opt. Soc. Am. **32**, 61 (1942).

[2] P. Kubelka and F. Munk, Zeits. f. tech. Physik **12**, 593 (1931).

[3] L. Amy, Rev. d'optique **16**, 81 (1938).

[4] Duntley's equation reduces to the above Eq. (3) for $P=0$, $Q=1$ (see reference 1). See also D. R. Duncan, Proc. Phys. Soc. **52**, 380 (1940).

While Eqs. (1) and (2) can be expressed in a form convenient for use and are sufficiently accurate for some purposes, the general case of the translucent sample is better described by the improved theory of Duntley. Equation (3), however, has been found by the author to be very satisfactory for the treatment of opaque or nearly opaque samples. By means of Eq. (3), the spectrophotometric curve representing the reflection of an opaque sample containing several pigments

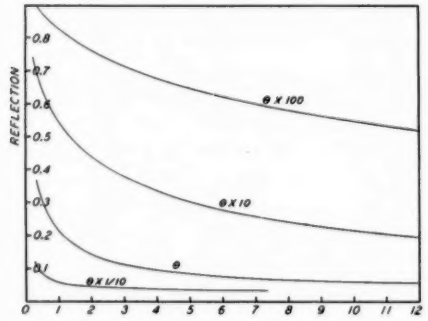

FIG. 1. Graph relating the measured reflection R' and the θ of Eq. (8).

whose constants are known may be calculated. The calculation can be made as easily and accurately as the calculation of the transmission curve by means of Beer's law of a sample containing several dyes.

From Eq. (3), it is evident that the reflectance is a function of μ/ρ. It is, therefore, impossible to determine the true value of either μ or ρ from reflection measurements alone. However, as long as only the calculation of reflectance cases is desired only the relative values of the constants and not the true values are necessary. As will be shown later, the true or absolute constants may easily be determined from a transmission measurement. The respective advantages of the relative and absolute sets of constants will be discussed later.

In order to predict the color of a mixture of pigments, it is assumed that the μ's and ρ's for the individual pigments are additive in proportion to their respective concentrations. That is,

$$\mu = C_1\mu_1 + C_2\mu_2 + C_3\mu_3 + \cdots = \Sigma C_i\mu_i, \quad (4)$$

$$\rho = C_1\rho_1 + C_2\rho_2 + C_3\rho_3 + \cdots = \Sigma C_i\rho_i, \quad (5)$$

where the subscripts indicate the several different pigments. The problem is thus reduced to the determination of the constants μ and ρ for the pigments to be used. Before illustrating the method for determining these constants, the effect of the surfaces of the specimen will be considered.

3. THE SURFACE CORRECTION

The spectrophotometric measurements here reported were made with a General Electric recording spectrophotometer.[5] In this instrument the light incident upon the sample is approximately parallel and the diffusely reflected light is all collected by the integrating sphere for measurement. In the instrument used by the author, about half the specularly reflected light is lost through the entrance hole of the integrating sphere.[6] The relation between the reflection R' from a sample as measured by the spectrophotometer, and the "reflectance" R which the sample would have if measured in a transparent medium having the same index of refraction as the sample, can be expressed as

$$R' = \frac{k_1}{2} + (1-k_1)(1-k_2)\frac{R}{1-k_2R}. \quad (6)$$

In this expression,[7] k_1 is the fraction of the incident light which is reflected from the front surface of the sample, and can be found from Fresnel's law for normal incidence for a change of index of refraction from 1 to n,

$$k_1 = \left[\frac{n-1}{n+1}\right]^2. \quad (7)$$

Of this fraction, only one-half is measured by the spectrophotometer, and only $(1-k_1)$ of the incident light enters the reflecting sample. The constant k_2 is the fraction of the light incident *diffusely* upon the surface of the sample from the inside which is reflected, so that the fraction $(1-k_2)$ emerges from the sample into the integrating sphere. For the plastic material used by

[5] J. L. Michaelson, J. Opt. Soc. Am. **28**, 365 (1938).

[6] See also A. E. Parker, *Symposium on Color*, p. 53, published by the American Society for Testing Materials (1941).

[7] See also J. W. Ryde, Proc. Roy. Soc. **A131**, 451 (1931). Ryde's Eq. (59) reduces to the above Eq. (6) for (his) $T = T' = 0$, $R' = R$.

the author (polystyrene, index of refraction $=1.59$), $k_1 \sim 0.05$, and $k_2 \sim 0.4$. The seemingly large value of k_2 was determined by trial, and a little consideration makes this value appear quite reasonable.[8] By means of the surface correction given by Eq. (6), reflection measurements made in air can be used with the fundamental reflectance Eq. (3), thus eliminating the inconvenience of oil baths and similar devices. Equations (3) and (6) can be combined so that it is possible to go from μ/ρ to R' and vice versa in one step. If

$$\theta \equiv \frac{\mu}{\rho} = \frac{\sum C_i \mu_i}{\sum C_i \rho_i}, \tag{8}$$

then the relation[9] between θ and R' is given by Fig. 1. All reflection curves given in this paper are relative to a smoked surface of MgO.[10]

4. THE CALCULATION OF CONSTANTS

The method for calculating the constants μ and ρ for pigments will now be described. One measurement must, of course, be made for each constant to be determined, and furthermore, if the absolute set of constants is desired, it is necessary to begin with a transmission measurement. In the calculations illustrated, it has been the author's practice to use 1 percent as the unit of concentration for dyes and pigments, and one-tenth inch as the unit of length.

Given a molding 0.1 inch thick containing a concentration C_D of a dye, a transmission measurement will determine the absorption coefficient μ_D at any desired wave-length by the use of the equations

$$T' = (1-k_1)^2 \frac{T}{1-k_1^2 T^2} \tag{9}$$

and

$$T = \exp(-\mu_0 - \mu_D C_D). \tag{10}$$

In these equations T' is the measured transmission of the sample, T is the transmittance, k_1 is given by Eq. (7), and μ_0 is an absorption coefficient to be assigned to the undyed plastic. The terms transmission and transmittance are used in the same sense as explained above for the corresponding terms reflection and reflectance. To the approximation that $k_1^2 T^2 \ll 1$, the transmission equation may be written

$$T' = T_0 \exp(-\mu_D C_D), \tag{11}$$

where

$$T_0 = (1-k_1)^2 \exp(-\mu_0). \tag{12}$$

T_0 is given by a transmission measurement of an undyed molding, as shown in curve A of Fig. 2. The transmission curve of a molding containing 0.01 percent of a dye is shown in curve B. The absorption coefficient μ_D as calculated from Eq. (11) is also given at 20 $m\mu$ intervals in Fig. 2.

With the absorption coefficient for the dye determined, the absorption and scattering coefficients for a pigment may now be found. Two moldings are necessary. The most convenient ones are a molding containing only the pigment and another containing a mixture of the pigment and dye. The reflection curves for two such moldings are given in Fig. 3. Curve A is of a molding containing 0.5 percent white pigment, and curve B of a molding containing 0.5 percent white pig-

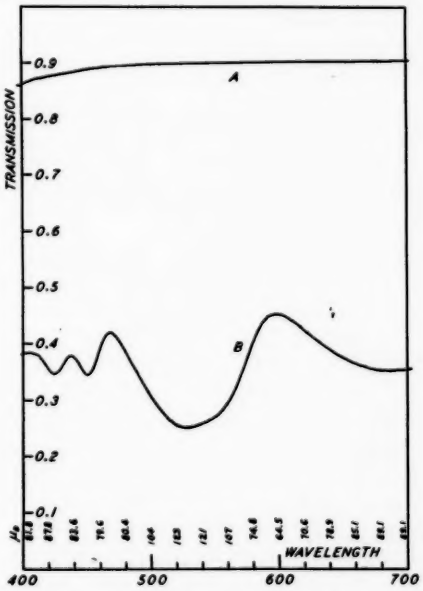

FIG. 2. Calculation of dye constants. Curve A: undyed molding; curve B: 0.01 percent dye. The absorption coefficients μ are calculated from Eq. (11).

[8] See also J. W. Ryde and B. S. Copper, Proc. Roy. Soc. **A131**, 464 (1931), especially page 467.

[9] D. R. Duncan, reference 4, bases his calculations on $\theta \equiv e/\mu$. The use of Eq. (7) has been found by the author to be more convenient.

[10] U. S. Department of Commerce, National Bureau of Standards, Letter Circular, LC-547.

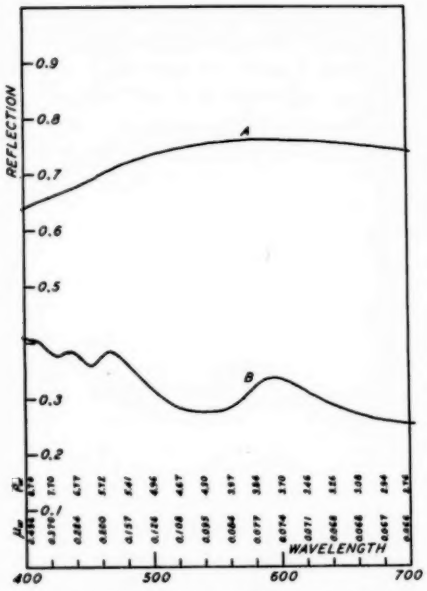

FIG. 3. Calculation of constants of white pigment. Curve A: 0.5 percent white pigment; curve B: 0.5 percent white pigment+0.01 percent dye. The scattering coefficients ρ are calculated from Eq. (15) and the absorption coefficients μ from Eq. (13).

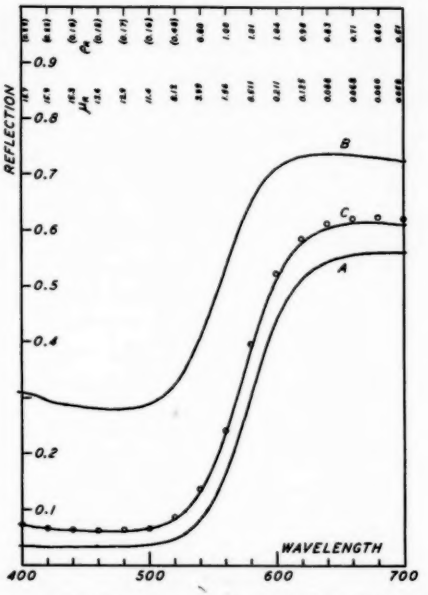

FIG. 4. Calculation of constants of red pigment. Curve A: 0.5 percent red pigment; curve B: 0.1 percent red+0.4 percent white; curve C: 0.4 percent red+0.1 percent white. The constants μ and ρ for the red pigment are determined by means of Eqs. (16) and (18). The constants are used to calculate the position of curve C.

ment and 0.01 percent of the dye whose absorption coefficients were determined above. For curve A, Eq. (8) gives

$$\theta_W=\frac{C_W\mu_W}{C_W\rho_W}=\frac{\mu_W}{\rho_W}, \tag{13}$$

and for curve B,

$$\theta_{W,D}=\frac{C_W\mu_W+C_D\mu_D}{C_W\rho_W}. \tag{14}$$

Then solving for ρ_W,

$$\rho_W=\frac{C_D\mu_D}{C_W(\theta_{W,D}-\theta_W)}, \tag{15}$$

and Eq. (13) may be used to find μ_W. The values for θ_W and $\theta_{W,D}$ are found by means of Fig. 1 using the reflection values of curves A and B, respectively. The values for μ_W and ρ_W as found by Eqs. (15) and (13) are given in Fig. 3. These equations and those which follow in this section assume that the absorption coefficient μ_0 of the base material is zero. The case for $\mu_0\neq 0$ is considered in Section 7.

The constants for any other pigment may now be found. Figure 4 shows the reflection curve of a molding containing 0.5 percent red pigment (curve A), and that of a molding containing 0.1 percent red pigment and 0.4 percent white pigment (curve B). For curve A,

$$\theta_R=\frac{C_R\mu_R}{C_R\rho_R}=\frac{\mu_R}{\rho_R}, \tag{16}$$

and for curve B

$$\theta_{W,R}=\frac{C_W\mu_W+C_R\mu_R}{C_W\rho_W+C_R\rho_R}. \tag{17}$$

Then

$$\rho_R=\frac{C_W}{C_R}\,\frac{\theta_{W,R}\cdot\rho_W-\mu_W}{\theta_R-\theta_{W,R}}, \tag{18}$$

and μ_R is found from Eq. (16). The μ and ρ values for the red pigment are shown in Fig. 4.

It will be noticed that the ρ values in Fig. 4 from 400 mμ to 520 mμ are given in parentheses. This is to indicate that these ρ values are subject to considerable inaccuracy since curve A approaches the value to be expected for surface reflection at these wave-lengths. θ_R is thus very large and a small inaccuracy in the reflection

causes a large uncertainty in θ_R, as given by Fig. 1. Thus ρ_R as given by Eq. (18) is subject to the same uncertainty. It is important to notice, however, that μ_R is still accurately determined in spite of the uncertainty of ρ_R. For, combining Eqs. (16) and (18),

$$\mu_R = \rho_R \theta_R = \frac{C_W}{C_R} \frac{\theta_{W,R} \cdot \rho_W - \mu_W}{\theta_R - \theta_{W,R}} \cdot \theta_R$$

$$= \frac{C_W}{C_R} \frac{\theta_{W,R} \rho_W - \mu_W}{1 - (\theta_{W,R}/\theta_R)}, \quad (19)$$

so that when $\theta_R \gg \theta_{W,R}$, μ_R is quite insensitive to θ_R.

In using the constants μ_R and ρ_R for calculating reflection values, it may be shown that the above-mentioned uncertainty in ρ_R is of little importance. This uncertainty will occur when the reflection is very small, which means that $\mu_R \gg \rho_R$. Therefore, if only a small amount of this pigment is used in a mixture with other pigments, the principal effect of this pigment will be given by the contribution of the term $C_R \mu_R$ to the total μ, and effect of the term $C_R \rho_R$ will be negligible. On the other hand, if a large amount of this pigment is used in a mixture, then the reflection will be very small so that considerable inaccuracy in θ results in only a small uncertainty in R'. This situation is, of course, to be expected, for if it happens that a ρ value cannot be determined accurately from reflection curves, then, when reversing the process, it is evident that a calculated reflection value should be quite indifferent to the value of ρ used.

The third curve of Fig. 4, curve C, is of a molding containing 0.4 percent red pigment and 0.1 percent white pigment. This curve may be used to check the constants calculated from the other two curves. The points along curve C are the points predicted by using the constants shown in the figure. In connection with the uncertainty of ρ_R, it may be noted that, at 500 mμ, the reflection of curve C is calculated to be 6.5 percent using $\rho_R = 0.16$ as given, whereas by using a ρ_R twice as large the reflection is calculated to be 6.9 percent, indicating that R' is quite insensitive to ρ_R at this wave-length. The cause of the discrepancy between the calculated and observed reflection values at longer wave-lengths is not evident, although it may be said that the experimental error in making up and molding pigment mixtures in the plastic is of an order of magnitude sufficient to account for the observed discrepancy, especially at high values of reflection.

It can be seen from Eq. (18) that when θ_R and θ_W (and therefore $\theta_{W,R}$) approach equality, the equations for ρ_R and μ_R become indeterminant. The accuracy with which the constants are determined, therefore, becomes poor when the reflection curve for the pigment approaches that for the white. For this reason, it is the practice in this laboratory, when calculating the constants for a new pigment, to make up a third molding containing the new pigment mixed with a black pigment whose constants are already known. The black pigment will alter the curve of the new pigment most where the latter has a high reflection, and thus an accurate determination of the constants can be made at these wave-lengths.

The constants found by the above equations may be termed the "absolute" set of constants. The principal advantage of the absolute constants is that the constants determined for dyes by use of Beer's law may be used directly when considering the opaque case. Thus, if one has a catalog of dye constants used primarily for calculations on transparent moldings, these same constants may be used for calculation of the reflection of mixtures of dyes with pigments. A lesser advantage of the absolute set of constants is that approximate calculation of the transmission and reflection of translucent moldings may be made.

The main advantage of a "relative" set of constants lies in the greater simplicity of the θ equation for most practical cases of color calculation on plastics, thus facilitating somewhat the actual calculations. This feature is quite important in routine work. A convenient set of relative constants is obtained by setting the scattering coefficient of the white pigment most commonly used equal to unity, thus,

$$\rho_W = 1. \quad (20)$$

This equation replaces Eq. (15). The absorption coefficient for the white pigment then becomes, by Eq. (13),

$$\mu_W = \theta_W. \quad (21)$$

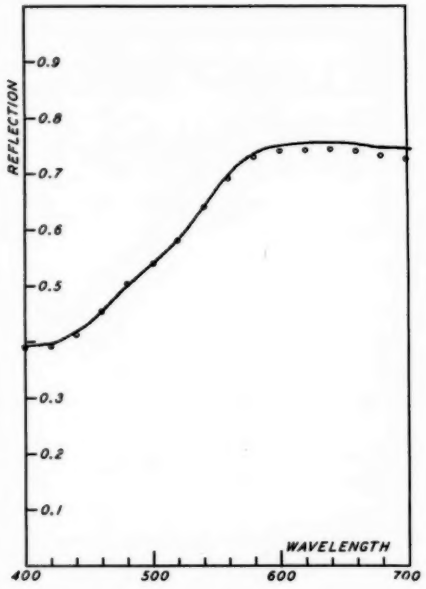

FIG. 5. Calculation of a pigment mixture, as carried out in Table I.

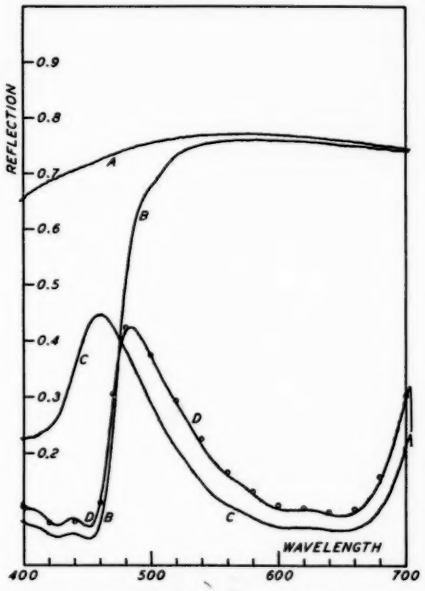

FIG. 6. Use of the relative constants. Curve A: 0.5 percent white pigment; curve B: 0.5 percent white pigment +0.05 percent yellow dye; curve C: 0.5 percent white pigment+0.05 percent blue dye; curve D: 0.5 percent white pigment+0.025 percent yellow dye+0.025 percent blue dye. The relative constants for the white pigments and the yellow and blue dyes are calculated in Table II. The constants can be used to predict the curve D, as illustrated by Table III.

For a dye mixed with a white pigment, Eq. (14) is simplified so that the absorption coefficient for the dye is given by

$$\mu_D=(\theta_{W,D}-\theta_W)\frac{C_W}{C_D}. \tag{22}$$

For the moldings of the red pigment whose curves are given in Fig. 4, the constants for the red pigment are given by

$$\rho_R=\frac{C_W}{C_R}\frac{\theta_{W,R}-\theta_W}{\theta_R-\theta_{W,R}} \tag{23}$$

and Eq. (16) for μ_R as before.

The choice of $\rho_W=1$ is convenient since a mixture of a colored pigment with white is the most accurate method in general for finding the constants for the colored pigments. Furthermore, white is by far the most commonly used pigment in colored plastics, so that calculation of the color of mixtures of pigments is somewhat simplified. The relative constants can be converted to absolute constants by multiplying both μ's and ρ's by the value of ρ_W at each wave-length.

5. THE CALCULATION OF THE COLOR OF PIGMENT MIXTURES

The calculation of a mixture of several pigments is accomplished by means of Eq. (8) relating θ for the mixture to the absorption and scattering coefficients of the individual pigments in the mixture. An example of the calculation of a pigment mixture is given in Table I for several wave-lengths, and illustrated in Fig. 5. The constants for the red pigment were determined from the curves of Fig. 4, and those for the yellow pigment from two similar curves. The actual spectrophotometric curve of a sample made containing these pigments is given for comparison.

Figure 6 illustrates four curves, three of which may be used to determine the relative absorption coefficients of the white pigment (curve A), the yellow dye (curve B), and the blue dye (curve C), with $\rho_W=1$. These constants may then be used to calculate the curve of the mixture (curve D). Several calculations are illustrated in Tables II and III.

6. THE CALCULATION OF COLOR MATCHES

With this method, a color match is obtained by approximating as closely as possible the spectrophotometric curve of the desired color. Inspection of the desired spectrophotometric curve as well as reference to the catalog of curves of the pigments on hand will indicate the several pigments which will be necessary to duplicate the desired color. The respective concentrations of the chosen pigments must then be calculated. An example will serve to illustrate the method.

Suppose the color to be matched is represented by curve A of Fig. 7. It is evident that four pigments, if the correct ones are available, will match the curve. White will be necessary to obtain the required opacity, black will lower the curve at all wave-lengths so that a fit at the red end of the curve is possible, a red or orange pigment will produce the drop between 560 mμ and 600 mμ, and yellow will give the second drop around 500 mμ. In Fig. 8, the accumulative result of adding these pigments in the order given above to the white pigment is illustrated. The concentration of black will determine the height of the curve between 620 mμ and 700 mμ, since the red and yellow pigments do not absorb significantly in this region. The concentration of white is first fixed from opacity considerations and then the concentration of the black can be determined by solving for C_B in the equation

$$\theta=\frac{C_W\mu_W+C_B\mu_B}{C_W\rho_W+C_B\rho_B}, \tag{24}$$

where θ corresponds to the reflection value desired at some wave-length between 620 mμ and 700 mμ. With C_B determined, the concentration of the red pigment can be found by solving for C_R in the equation

$$\theta=\frac{C_W\mu_W+C_B\mu_B+C_R\mu_R}{C_W\rho_W+C_B\rho_B+C_R\rho_R}, \tag{25}$$

where θ now corresponds to the reflection value desired at about 540 mμ. This is possible since the yellow pigment does not absorb appreciably at 540 mμ. Finally, the concentration of the

TABLE I. Calculation of the color of a pigment mixture. The calculations of the reflection value of a sample containing 0.5 percent white pigment, 0.015 percent red pigment shown in Fig. 4, and 0.025 percent yellow pigment are carried out in this table. The calculations are made by means of Eq. (8), and the results are compared with the actual curve obtained for the sample in Fig. 5.

λ	$0.5\mu_W$	$0.015\mu_R$	$0.025\mu_Y$	$\Sigma\mu$	$0.5\rho_W$	$0.015\rho_R$	$0.025\rho_Y$	$\Sigma\rho$	θ	R'
400	0.239	0.235	0.730	1.207	4.350	0.004	0.013	4.367	0.276	0.390
500	0.067	0.170	0.021	0.258	2.480	0.002	0.030	2.512	0.103	0.540
600	0.037	0.003	0.004	0.044	1.850	0.016	0.026	1.892	0.023	0.741
700	0.033	0.001	0.003	0.037	1.380	0.010	0.017	1.407	0.026	0.727

TABLE II. Calculation of "relative" constants. These calculations are given as an illustration of the calculation of the relative constants of a white pigment and two dyes by use of Eqs. (22) and (23). The data are taken from curves A, B, and C of Fig. 6.

	White pigment		Yellow dye				Blue dye			
λ	R_W'	$\theta_W=\mu_W$	R_Y'	θ_Y	$\theta_Y-\theta_W$	μ_Y	R_B'	θ_B	$\theta_B-\theta_W$	μ_B
400	0.643	0.052	0.077	5.65	5.60	56.0	0.225	0.895	0.843	8.43
500	0.745	0.025	0.678	0.040	0.015	0.15	0.287	0.555	0.530	5.30
600	0.766	0.020	0.766	0.020	0.	0.	0.070	6.60	6.58	65.8
700	0.745	0.025	0.745	0.025	0.	0.	0.220	0.935	0.910	9.10

TABLE III. Calculation of the color of a mixture. The constants calculated in Table II are used to predict the curve D of Fig. 6 by means of Eq. (8).

λ	$0.5\mu_W$	$0.025\mu_Y$	$0.025\mu_B$	$\Sigma\mu$	$0.5\rho_W=\Sigma\rho$	θ	R'
400	0.026	1.40	0.211	1.64	0.5	3.28	0.104
500	0.013	0.004	0.132	0.149	0.5	0.298	0.378
600	0.010	0	1.64	1.65	0.5	3.30	0.105
700	0.013	0	0.228	0.241	0.5	0.482	0.307

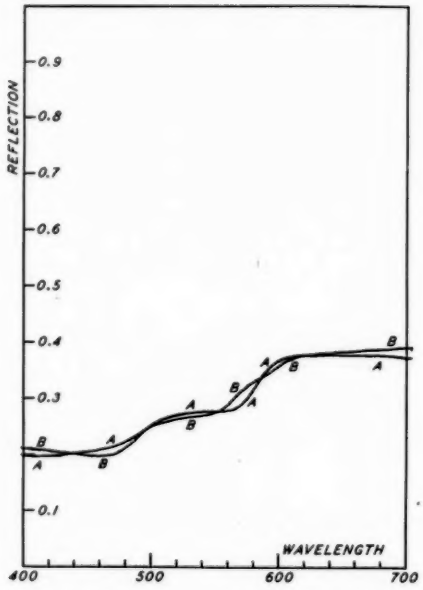

FIG. 7. Calculation of a color match. Curve B is the attempted duplication of curve A of the original.

yellow pigment may be found by solving for C_Y in a similar equation with the μ and ρ terms for the yellow pigment added to the numerator and denominator, respectively, and with θ corresponding to the reflection value desired at about 440 mμ. The fact that the scattering coefficients of the red and yellow pigments were neglected when determining C_B, and that of the yellow when determining C_R, introduces negligible errors in the calculation of the reflection curve in this case since C_R and C_Y are much smaller than C_W.

After finding the concentrations of the pigments as discussed above, one should calculate the reflection values at several intermediate wave-lengths to be sure that the correct shape of curve will result. If the shape is not correct, it is necessary either to select a more favorable pigment or to introduce an additional one to modify the curve. In actually matching the curve discussed above, a red pigment having the correct shape of cut-off between 560 mμ and 600 mμ was not available, so that it was necessary to approximate the curve by two red pigments thus forming two steps in this region. The match which resulted in this case is shown in curve B of Fig. 7. This match was quite acceptable visually.

In some cases it will be found impossible to separate the effects of the individual pigments as was done in the above example. In such cases one must either solve a set of linear simultaneous equations or proceed by trial and error. Suppose, for example, that two pigments, 1 and 2, are to be added to white, and that at one wave-length the reflection should correspond to θ and at another wave-length to θ'. Then the equations

$$\theta=\frac{C_W\mu_W+C_1\mu_1+C_2\mu_2}{C_W\rho_W+C_1\rho_1+C_2\rho_2}, \tag{26}$$

$$\theta'=\frac{C_W\mu_W'+C_1\mu_1'+C_2\mu_2'}{C_W\rho_W'+C_1\rho_1'+C_2\rho_2'} \tag{27}$$

may be solved for the two unknowns C_1 and C_2. By adding two pigments to white it is mathematically possible to obtain a desired reflection value at any two wave-lengths. With n pigments added to white the reflectance value may be fixed at n wave-lengths. While the equations will always give a solution, sometimes one or more of the concentrations will come out negative. This, then, is a mathematical solution which is not possible physically, and one must either choose

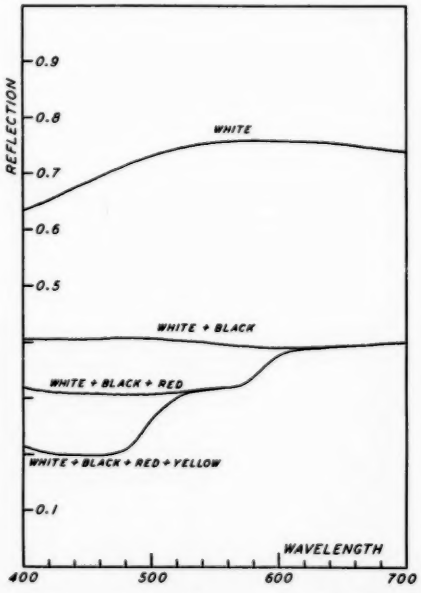

FIG. 8. Curves showing the accumulative effect of the various pigments added to white.

other pigments or select other wave-lengths at which the reflection is fixed.

7. ABSORPTION BY THE BASE MATERIAL

When the base material in which the pigments are dispersed is itself somewhat colored, it will be necessary to assign to it an absorption coefficient μ_0, which can be evaluated by transmission measurements. The θ equation will now have this term in the numerator. For example, Eq. (13) will become

$$\theta_W = \frac{\mu_0 + C_W \mu_W}{C_W \rho_W}, \tag{28}$$

and similarly for the others. Similarly, should the necessity arise, one may assign a scattering coefficient ρ_0 to the medium itself. These refinements complicate the calculations somewhat, but do not change the general procedure.

8. THE EFFECT OF OPACITY

Equations (13) and (16) say that the reflection from a sample containing one pigment is independent of the concentration of that pigment. Also, equations like (17) say that the color of a sample containing a mixture of pigments depends only upon the relative concentrations of the respective pigments and not upon the total concentration of pigment. The equations, however, are based upon the assumption that the sample is opaque, and also that the absorption coefficient of the medium is negligible compared with the absorption coefficient of the pigment. If μ_0 is not negligible, then an equation like (28) must be used, and hence the reflection is no longer independent of the pigment concentration.

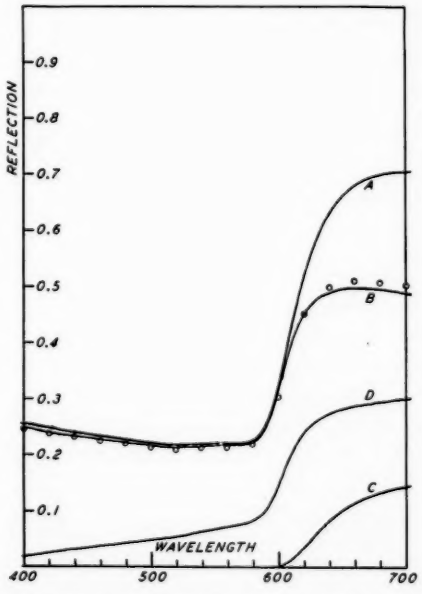

FIG. 9. The effect of opacity. Curve A: 0.5 percent concentration, reflection; curve B: 0.1 percent concentration, reflection; curve C: 0.5 percent concentration, transmission; curve D: 0.1 percent concentration, transmission. Curves A and B are essentially the same where the transmission (curve D) is small. An opacity correction has been applied in calculating the points along curve B.

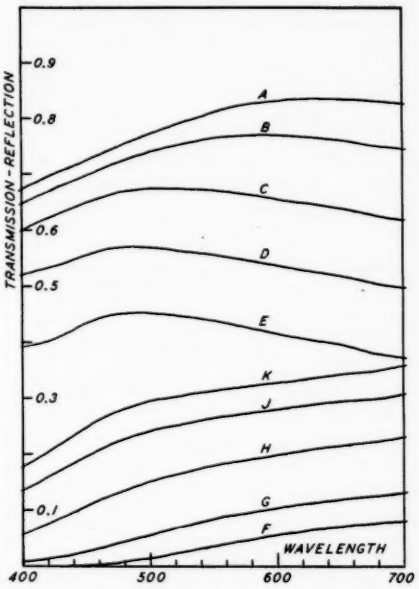

FIG. 10. Curves of the reflection and transmission of the white pigment, used for making the opacity correction. Curves A to E are reflection curves of 1.0 percent, 0.5 percent, 0.2 percent, 0.1 percent, 0.05 percent concentration of white pigment, respectively. Curves F to K are transmission curves of the same samples in the order given.

The total pigment concentration will determine what may be called the opacity per unit thickness. Whether or not the color of a sample is independent of the total pigment concentration or opacity depends upon how closely the conditions $T=0$ and $\mu_0=0$ are followed. In Fig. 9, transmission and reflection curves are shown for two samples containing 0.5 percent and 0.1 percent of the same pigment. For the wavelengths where the transmission of the less opaque

molding is small, the reflection agrees fairly well with that of the more opaque molding which contains five times as much pigment. However, where the transmission of the less opaque molding is larger, the two reflection curves no longer agree. Figure 10 shows similar reflection and transmission curves for various concentrations of a white pigment, illustrating that the reflection in this case is far from being independent of the concentration. In this case, however, the moldings obviously cannot be considered opaque until at least 0.5 percent concentration is reached, and even this has some transmission for red light. Furthermore, it is probable that the requirement that the absorption coefficient μ_0 of the base material be negligible compared to the absorption coefficient of the pigment μ_W is not obeyed. It is possible, of course, as pointed out above, to introduce μ_0 into all the equations, but the author has not considered this additional complication to be sufficiently necessary when working with polystyrene.

An approximate correction for the variation in reflection of the white pigment with concentration as illustrated by Fig. 10 may easily be made by introducing an additional absorption coefficient (positive or negative with respect to the 0.5 percent concentration curve *B*) into the calculations. This was done in order to plot the points along curve *B* of Fig. 9, using a correction based upon curves *B* and *D* of Fig. 10. It will be seen that the correction automatically becomes unimportant when the absorption becomes great enough to make the molding essentially opaque.

9. SUMMARY

The so-called two-constant theory describing the optical properties of pigmented media has been discussed in detail for the special case of an opaque sample. The conditions of reflection measurement which obtain in a General Electric recording spectrophotometer were discussed, and an appropriate surface correction was incorporated into the formulae so that the correction is made automatically. A method for determining the optical constants of dyes and pigments is given which is not too complicated for routine industrial use. Examples are given of the calculation of the color of pigment mixtures, and of the method used by the author for making color matches. Special phases of the theory are discussed, such as the effect of opacity and the accuracy of determining the constants.

Proceedings of the Twenty-Seventh Annual Meeting of the Optical Society of America

HOTEL PENNSYLVANIA, NEW YORK CITY, OCTOBER 30–31, 1942

THE twenty-seventh annual meeting of the Optical Society was held concurrently with meetings of the American Mathematical Society and the Society of Rheology. A significant feature of this meeting was the number of members and non-members who were apparently attending their first meeting of the Society. It seemed to be generally agreed that interest in optics had been greatly stimulated by various war activities on the part of many for whom optics had hitherto seemed of minor importance.

SYMPOSIUM OF INVITED PAPERS ON OPTICAL INSTRUMENTS

The meeting was opened by President Worthing on Friday, October 30, with a symposium of invited papers on "Optical Instruments," consisting of five papers.

The important advances in the development of the microscope objective from the time of its invention by the Dutch spectacle makers Hans and Zacharias Jannsen, to the present, were described by A. H. Bennett. The placing of two convex lenses in such relative positions that one would magnify the image of the other followed soon after the invention of the telescope. The historical development of the microscope from this primitive instrument to one having ten or more elements was traced.

Important steps in the evolution of the instrument were discussed by the speaker, among which were the devising of microscope objectives composed of compound lenses; the discovery of methods of achromatism and correction of spherical aberration in the period 1820–1830 by employing combinations of lenses of different glasses and different curvatures; the work of early American microscope makers in increasing numerical aperture; the invention in the United States of the oil immersion objective; the invention of Jena optical glasses and the work of Abbe, one result of which was the apochromatic objective. Present day developments were discussed in some detail.

The second paper of the symposium, by Arthur C. Hardy, was concerned with flux calculations in optical systems. The treatment was carried through to its final stages in energy units, relating the irradiance on a surface to the radiant emittance of the source. A general equation was derived for the irradiance at any point on the axis of an optical system; and the irradiance was shown to depend only on the radiant emittance of the source and the angle of the cone converging at the point in question, neglecting losses in the optical system due to absorption and reflection.

In discussing the design of visual instruments, it was pointed out that the irradiance of the retina of the eye is controlled by the size of the cone of light having its base at the pupil and its apex on the retina. The angle of this cone varies with the size of the pupil. The irradiance on the retina is about one percent of the value it would have if the retina were placed in immediate contact with the light source, neglecting absorption by the media of the eye. For a given radiant emittance, no optical instrument will increase the irradiance of the retina; the irradiance may be decreased if the limiting aperture of the system is within the instrument rather than the eye. In non-visual instruments using photographic plates, photoelectric cells, and similar physical detectors of radiation, the restrictions that have to do with the size of the exit pupil do not apply.

With the principles set forth, the performance of an optical system can usually be estimated in advance of its construction and use, assuming the necessary data are available.

Various methods of measuring the transmission of light through optical instruments were reviewed by D. B. McRae, and their advantages and disadvantages were discussed. All measuring methods were shown to be based on the fundamental equation derived in the previous paper. These methods were applied to the discussion of three types of optical systems—systems with finite focal length, e.g., photographic lenses; systems with infinite focal length, e.g., telescopes;

and systems which dispense light into its spectral components, e.g., spectrometers.

In general, two methods have been used to measure the transmission of optical systems; (1) a comparison of entrance and exit pupil brightness, using a diffuse radiator at one position and a photometer at the other, (2) a comparison of the brightness of a more or less distant object with the brightness of its image.

The first method, very commonly used, is less reliable than the second because of reflection errors. Repeated inter-reflections between various elements of the system were shown to be a serious source of error, and to affect considerably the contrast of the image. A method for measuring contrast for systems with finite focal length was also briefly described.

James G. Baker described some applications of fifth-order theory to the design of optical systems. In designing certain systems which call for high degrees of perfection, the fifth-order (and in some cases the seventh- and higher order) errors must be reduced to unobjectionable magnitude.

An examination of the fifth-order image errors indicates the existence of three conditions relating skew rays to meridian plane rays, quite analogous to the Petzval sum of the third order. In a few cases it has been possible to set up the three conditions analytically. Some useful formulas leading to the understanding of the nature of the fifth-order terms were described, and several applications noted. The significance of certain numerical results obtained from lens systems of the above kind was discussed.

The growing importance of photographic methods in scientific work has made more insistent the demand that methods be provided for specifying the performance of photographic objectives in terms of engineering data. I. C. Gardner stated that this demand has been particularly urgent from those who construct topographic maps from airplane photographs because the success of such an undertaking is particularly dependent upon the performance of the lens. Accordingly, the National Bureau of Standards has developed a standardized procedure for specifying the quality of definition in terms of resolving power. Special charts and a special camera are used; illustrations of these were shown. The resolving power is read from a negative of the charts made through the lens to be tested, a visual examination of the image not being considered satisfactory for testing a lens to be used for photographic purpose. A test of resolving power has been incorporated in specifications used by the government when letting contracts for airplane-mapping projects. These specifications, which have been in use for several years, probably represent the first attempt to write specifications for a photographic lens which will be entirely functional, are based upon performance, and are largely free from subjective influence. A method of testing lenses which is available for amateurs skilled in photographic technique has also been developed.

Joint Luncheon

At the joint luncheon of the American Mathematical Society, the Society of Rheology, and the Optical Society of America, the guest speaker, Dr. Frank B. Jewett, was introduced by Dr. H. E. Ives. Dr. Jewett discussed the functions and organization of the Office of Scientific Research and Development and the National Defense Research Committee. The O.S.R.D. was described by the speaker as the biggest industrial research project ever undertaken; as an indication of the magnitude of the undertaking, an expenditure of about $100,000,000 will be administered by this organization during the present fiscal year. From its inception, the policy of the N.D.R.C. has been to assign work to existing institutions of learning, scientific institutions, and industrial laboratories. As a consequence, it has been unnecessary to build up a great new organization which would require the disruption of present facilities. In only a few instances has it been necessary to create new laboratory facilities on a large scale.

The emphasis of the work administered by the O.S.R.D. has undergone a change during the past year; as certain outstanding projects have emerged from a mass of research activities, more and more attention is being given to the development of the practical application of these new devices.

The functions of the National Academy of Sciences as the official scientific adviser to the Government were also outlined.

Joint Symposium with the American Mathematical Society on Mathematics in the Field of Optics

Dr. R. M. Foster of the Mathematical Society was Chairman of the joint symposium of invited papers held on Friday afternoon, October 30.

The first paper on this program, by Dr. J. L. Synge, discussed the theory of the Schmidt telescope. The principle of this instrument, and the mathematical reasoning involved in its development, were described. A spherical mirror gives an image free of astigmatism; a correcting plate is introduced to remove axial spherical aberration. The plate also corrects coma over a wide field. This correcting plate is almost plane-parallel, only a slight depth of figuring on one side being necessary. The solid Schmidt, where the spherical reflecting surface and the correcting plate are combined into a single homogeneous piece of glass, is one of the simplest possible optical instruments.

The essentials of Dr. Synge's paper were; first, the direct use of the T function, or angle-characteristic, following the technique originally used by Hamilton almost a hundred years ago; and second, the expansion in terms of a small parameter which refers simultaneously to the small inclination of the rays to the axis and to the small depth of figuring of the correcting surface.

The determination of the T function is almost an impossibility with complex systems; the solid Schmidt, because of its simplicity, is ideally suited to this treatment. The equation of the rays is first given to the third order, and all defects of this order may be studied directly. The method makes it possible to proceed to higher orders without difficulty.

The mathematics of turbid media was discussed by Dr. S. Q. Duntley from the historical point of view. It was pointed out that the principle of "self-illumination" was recognized by Schuster in 1903 in connection with his treatment of the influence of radiation on the transmission of heat. This was expressed in completely general form by King (1913) as a first-order integral equation of the second kind. King's attempt to treat the atmospheric case failed to produce a solution in accord with observation because of certain necessary but damaging assumptions. The general solution stands today an unanswered mathematical challenge. Practical meteorologists make the best of Kochmeider's interpretation of the approximate treatment by Wiener. Many industrially important turbid media including plastics, paint, printing ink, paper, and textiles may be treated by engineering solutions stemming from the original special case treatment by Schuster.

The development during the last decade of synthetic polarizing sheets, which are now available in commercial quantities, has greatly increased the practical importance of optical systems whose function is to control the state of polarization of the light passing through them. Dr. R. Clark Jones described a matrix calculus for the treatment of such systems. The use of the calculus has led to some general theorems about the properties of these systems, which in many cases facilitate the calculation of the properties of particular systems.

The first part of the talk was devoted to a brief description of the matrix calculus. Following this, it was shown how the matrix treatment makes possible a simple proof of some general equivalence theorems. Finally, the application of the calculus to the optical system described many years ago by E. Reusch was outlined. Reusch's system consisted of a large number of retardation plates so oriented that the system as a whole exhibited only optical activity.

The final paper of the symposium on mathematics in the field of optics was presented by Professor Parry Moon. It was stated that methods of calculating illumination are important, not only in the design of better lighting but also in many problems connected with projection systems, photography, and meteorology. The paper outlined the status of the subject, and indicated the kind of developments in illumination calculations that have been made during the past five years. It is convenient to set up the general problem of illumination calculation in terms of a unit sphere so that spherical trigonometry becomes an important tool. The general expression is then used in the consideration of the uniform rectangular source and the uniform triangular source. It is also used in determining indoor and outdoor illumination from the non-uniform skies that occur in nature.

Another item of recent interest is the calculation of illumination from arrays of sources, such as the evenly spaced rows of fluorescent lamps used in many modern lighting installations. The calculation of the illumination from such systems has hitherto consisted in the laborious process of adding the effects of the individual sources. A recent investigation, however, proves that the array can be imagined replaced by an equivalent uniform ceiling, and the errors introduced by this approximation are entirely negligible in practical cases.

Field theory, which has been a powerful ally in the treatment of various branches of physics, has been applied to illumination calculations. It gives promise, although advances along this line in the past five years have not been noteworthy. Much has been accomplished, however, in the treatment of multiple reflections of light. The Hilbert-Schmidt theory of integral equations has been applied, and a number of new results have been obtained. From a practical standpoint, the most important recent advance has been the solution of the inter-reflection problem for the cylinder of arbitrary cross section with ends. This advance allows the calculation of illumination in artificially-lighted rooms where reflection factors are so high that multiple reflections from walls, ceiling, and floor are important. Previously, such problems could be handled only by extremely laborious approximate methods or by experiments on scale models. The integral-equation method has also been applied to daylight illumination in light-wells, though the important problem of inter-reflections in rooms lighted from side windows still baffles the investigator.

The speaker pointed out that adequate methods are now available for the solution of many illumination problems. Some of these methods date back to Lambert, others are new developments. The ideal of the subject as a complete, unified discipline is still far from realization, though recent developments bring us closer to that goal.

Annual Dinner and Award of the Adolph Lomb Medal

On Friday evening, a joint dinner was held for the members of the American Mathematical Society, the Society of Rheology, the Optical Society of America, and their guests. Officers of the three societies were introduced to the audience by Professor Worthing. Professor Marston Morse of the American Mathematical Society spoke briefly on the present change which mathematics is now undergoing. Mathematicians are turning from individual work of purely theoretical nature to the field of applied mathematics which calls for collaboration with physicists and workers in other fields.

Dr. W. B. Rayton, Chairman of the Committee on Award of the Adolph Lomb Medal, explained the establishment of this medal in honor of a charter member who had made great contributions to the Society. The medal is awarded to a candidate who has made noteworthy contribution to the cause of optics before attaining the age of thirty. The speaker stated that the committee was particularly fortunate in its choice of a young astronomer at the Harvard College Observatory who felt himself impelled to develop new methods for designing lenses in order to work in his chosen field. President Worthing then formally bestowed the medal on Mr. James G. Baker. The Medalist responded briefly, expressing his appreciation of the award, and mentioning the profits which will be reaped by astronomy as a result of the present wartime development of new materials and concepts.

G. A. Ellestad presented a popular discussion of patents, including such topics as the requisites of patentability, the application for a patent, and the procedure in the patent office. The matters of patent claims, infringements, and licenses were discussed with the help of illustrative examples. Reference was made to some optical patents which are of historical interest, particularly British Patent No. 721, issued in 1758, for the achromatic lens. Lantern slides were shown depicting some inventions which involved some unusual applications of optics.

Business Session

A brief business session was held on Saturday morning, October 31, President Worthing presiding. Formal reports of the Secretary, Treas-

urer, and Editor of Publications for the calendar year 1941 were accepted and placed on file.

Contributed Papers

Sessions for the reading and discussion of contributed papers were held on Saturday, October 31. The authors' abstracts of these papers are appended.

Registration

There were 226 persons registered at this meeting of the Optical Society, and doubtless many others present who did not register.

Meeting of the Board of Directors

A meeting of the Board of Directors was held on Thursday, October 29, 1942. Minutes of the meeting are appended.

Minutes of the Twentieth Meeting of the Board of Directors Optical Society of America, Incorporated

Hotel Pennsylvania, New York City, October 29, 1942

In addition to the transaction of routine business, the following items of general interest to members of the Society were taken up.

Announcements by Secretary

Results of letter ballots:

1. Approval of appointment of W. B. Rayton, R. C. Gibbs, and L. A. Jones as members of the Finance Committee.
2. Approval of appointment of Rudolf Kingslake (Chairman), Norman F. Barnes, Victor Chalupski, I. C. Gardner, Walter Granville, and David L. MacAdam as members of the Program Committee for the October, 1942 meeting.
3. Approval of resolution to increase the subscription price of the Journal from $6.00 to $7.00 in the case of domestic non-members, and from $6.60 to $7.70 in the case of foreign non-members.
4. Approval of appointment of Dorothy Nickerson (Chairman), Harry Nelson, and Glenn A. Fry as members of the Program Committee for the winter meeting in 1943.

Membership

The Secretary reported that, since January 1, 1942, 5 members had died, 185 new members had been elected, and 13 former members had been reinstated. The total membership is now well over 1200. The Board voted to transfer 73 associate members to regular membership.

Increase in Membership Dues

On the basis of a report covering several months of study by the Finance Committee, the Board voted to amend the By-Laws so as to increase the dues of associate members from $5.00 to $6.00, and the dues of regular members from $7.50 to $8.50, effective January 1, 1943. With this increase, the budget for 1943 is in balance despite the loss of foreign subscriptions, the increases in printing costs, and the enlargement of the Journal.

Appointments

The following appointments were made:

Nominating Committee for October, 1943, election:

K. S. Gibson, *Chairman*,
R. Bowling Barnes,
O. S. Duffendack,
Glenn A. Fry,
H. Keiffer Hartline.

OSA Representatives on the Inter-Society Color Council, for a term to expire in October, 1944:

R. C. Gibbs, *Chairman* (voting delegate),
I. H. Godlove (voting delegate),
D. B. Judd (voting delegate),
(Mrs.) Blanche Bellamy,
E. Q. Adams,
W. C. Granville,
A. C. Hardy,
L. A. Jones,
Parry Moon,
Dorothy Nickerson.

OSA Representatives to the U.S.N.C. of the I.C.I., for a term to expire in November, 1945:

Frank Benford, *Chairman*,
L. A. Jones,
D. B. Judd.

Program Committee for the Summer Meeting, 1943:
G. R. Harrison, *Chairman*
(additional members to be appointed later).

Arthur C. Hardy, *Secretary*

PROGRAM OF SESSIONS

(TITLES AND ABSTRACTS OF PAPERS)

Symposium of Invited Papers

OPTICAL INSTRUMENTS

Georgian Room

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9. **New Methods of Calculating Illumination.** PARRY MOON, *Massachusetts Institute of Technology.*

Contributed Papers

10. A Crystal Axis Goniometer. J. W. FORREST AND H. W. STRAAT, *Bausch & Lomb Optical Company.*

An improved form of crystal axis goniometer has been built which locates the position of the crystal axis according to the method described by Gumlich and used by Brodhun and Schonrock.* Other instruments of this same type have been described but because of their vertical or tilting sample table only small crystals could be conveniently examined. The present form of instrument differs in that its table is horizontal instead of vertical and does not tilt. This condition is realized by making the telescope, collimator, and source move about a horizontal axis as a single unit. Because of this arrangement, crystals as thick as six inches may be examined. The present form of the instrument is capable of locating the position of the axis within ten seconds of arc. It was developed by the Bausch & Lomb Optical Company working in conjunction with Dr. F. H. Bates of the National Bureau of Standards and Mr. D. W. Mann of Lincoln, Massachusetts.

* Brodhun and Schonrock, Zeits. f. Inst., December, 1902.

11. Analysis of Errors in a Reflecting Prism. PAUL W. STEVENS, *Eastman Kodak Company.*

A reflecting prism, whose surfaces are in error, may be considered as a system composed of a perfect prism and a wedge of small angle in sequence. By analyzing the deviations of rays of light in such a wedge, the performance of the system over a large range of incident angles may be determined. It is convenient to resolve the errors into components parallel and perpendicular to the principal section of the prism. The perpendicular component is commonly known as pyramid error, while the parallel component is a measure of the errors in the magnitudes of the angles. These principles will be applied in analyzing the simple isosceles reflecting prism.

12. A Method of Automatically Forming Three-Dimensional Models From Stereo-Images. LOUIS A. SCHOLZ, 1st. Lt. A.A.F. A.U.S.

An instrument is described for automatically translating stereo-pairs (negatives or positives) into three-dimensional models.

13. Computation of Polynomial Curves by Summation of Finite Differences. HAROLD F. BENNETT *Eastman Kodak Company, Hawk-Eye Works.*

An improved method is described for use with an adding or calculating machine in computing a series of points on a polynomial curve. The paper is addressed to computers who may wish to use the method, and all derivations are

relegated to the appendix. The method was developed when it was required to compute points on aspheric lens curves. It is equally applicable to cams and other curves and probably to much statistical material. In the case of irrational functions, if they can be approximated by a polynomial, the polynomial can be computed by this method and points on the irrational curve thus approximated. The method is modified from the classical method by writing down only one out of every three of the first and second differences. This saves time of writing and of entering numbers into the keyboard. The third and fourth differences are adjusted so that one numerical value serves for three successive difference values, and of these adjusted differences only one out of three is written, the other two being implicit in the computing routine. Thus only one value is written in these two orders where nine were written before. By a further approximation, one out of 27 of the fifth and sixth differences and one out of 81 of the seventh and eighth differences are written. Formulas are given whereby the leading differences are computed in terms of the constant coefficients of the polynomial. These formulas have been determined for polynomials up to the eighth degree. In addition, they are given in terms of the differences derived from $n+1$ equi-spaced points for the purpose of computing an nth degree curve through these points. Two sources of error are discussed, and quantitative expressions given for predicting their magnitude. They are the errors due to the rounding off of decimals and the errors due to the approximations in the method itself.

REFERENCES: Newcomb, *Logarithmic Tables* (Henry Holt, 1889). Sect. 25 and 26 is brief and clear. To mention two of many others: Whittaker and Robinson, *The Calculus of Observations* (Blackie & Son, 1932), pp. 2–7; and Rietz and others, *Handbook of Mathematical Statistics* (Houghton Mifflin, 1924), 34ff.

14. Mercury Arc Lamps: Effect of Electrode on Energy Distribution. WILLIAM THEODORE ANDERSON, JR., *Hanovia Chemical & Mfg. Company.*

While studying the energy distribution of radiation from differently constructed high pressure mercury vapor arc lamps in quartz it was noted that the work function of the electrodes and the operating temperature of the electrodes appeared to have a marked effect upon the spectral energy distribution of the lamps. In order to test this, a number of special lamps, identical excepting for the chemical constituents, work function, and temperature of the electrodes, were constructed and examined. It was found that for most efficient operation and for maximum ultraviolet production, a lamp with electrodes of very low work function and operating at relatively low temperatures is indicated. Life tests upon the lamps have demonstrated that for the same electrical input the temperature at which the electrode must operate has a marked influence upon the rate of deterioration. The rate and extent of loss in higher frequency radiation (short waved ultraviolet) increases with electrode temperature. The lost radiation is emitted in approximately equal amount as long waved infra-red. There is not any measurable diminution in total radiation with usage.

15. Electric Dichroism of Kaolin Suspensions. HANS MUELLER AND HARRY A. HELM, *Massachusetts Institute of Technology.*

In contrast to Bentonite clays, which show a large Kerr effect[1] and a small dichroism, suspensions of kaolin become very little birefringent but noticeably dichroitic under the influence of an electric field. When light from a steady source passes through a kaolin suspension while it is subjected to a transverse alternating field of low frequency it is found that the transmitted intensity has a modulated component which vibrates with twice the field frequency. Investigations of several monodisperse suspensions with different particle sizes show that the intensity of the modulated component increases and approaches saturation with increasing field intensity; the modulation disappears above a critical frequency which is the higher the smaller the particles. The dependence of the effect on the polarization of the incident light is especially interesting in as much as the modulation vanishes for a critical polarization angle. This angle is found to change with the particle size and the frequency of the field. The results demonstrate that measurements of dichroism in alternating fields offer a simple method for the determination of particle size in certain classes of colloids.

[1] H. Mueller and B. W. Sakmann, J. Opt. Soc. Am. **32**, 309 (1942).

16. Structural Interpretation of the Spectra of Various Derivatives of Different Hemins and of Cytochrome *c* and Hemoglobin. DAVID L. DRABKIN, *Medical School, University of Pennsylvania.*

Evidence collected upon the visible absorption spectra of cyanide, pyridine, globan (denatured globin), carbonyl, and carbonyl globan derivatives of different hemins (namely ferroproto-, ferromeso-, and ferrocoprohemin) justifies the following interpretations: (1) The spectra fall into three pattern groups, the shape and intensity of absorption being determined by the nature of the groups coordinating with the hemin iron. The three absorption patterns are characterized, respectively, by the spectra of the cyanide, pyridine (or globan), and carbonyl (or carbonyl globan) derivatives. (2) The wave-length location of the two bands (maxima) in the spectra of the various derivatives is, on the other hand, largely a function of the hemins themselves. The maxima and indeed the whole visible absorption curves of the derivatives of ferroprotohemin are shifted appreciably (order of 110A) towards the longer wave-lengths in comparison with the spectra of ferromeso- and ferrocoprohemin. The only obvious difference in the structures of the three hemins is in the groups substituted in positions 2 and 4 (Fischer's notation applied to iron porphyrins of etioporphyrin type III). Meso- and coprohemin have, respectively, ethyl and propionic groups, whereas protohemin has unsaturated vinyl radicles in these positions. The wave-length location of the maxima and the absorption spectra of corresponding derivatives of ferromeso- and ferrocoprohemin are practically identical. The shift in absorption towards the longer wave-lengths in the spectra of ferroprotohemin derivatives is therefore ascribed to the double bond in the vinyl groups, whose

presence increases the number of conjugated double bonds in the system. The role of the latter type of bonding in the shift of absorption towards longer wave-lengths was disclosed previously in the spectra of polyene derivatives, studied by Hausser, Kuhn, and their associates.[1] The spectra of cyanide, pyridine, and carbonyl derivatives prepared from hemoglobin in alkaline solution in the presence of a reducing agent are practically identical, both as to shape and wave-length location, with the spectra of corresponding derivatives prepared from ferroprotohemin. It is well-established that hemoglobin contains protohemin in its structure. On the other hand, the maxima of the spectra of cytochrome *c* and its derivatives are found in wave-length regions characteristic of derivatives of ferromeso- and ferrocoprohemin. It is deduced that cytochrome *c* does not contain in its structure an unmodified protohemin with free vinyl groups.

[1] K. W. Hausser, Zeits. f. tech. Physik **15**, 10 (1934). K. W. Hausser, R. Kuhn, et al. Zeits. f. physik. Chemie **B29**, 363, 371, 378, and 384 (1935).

17. A Metric for Colorspace. DOMINA EBERLE SPENCER, *Massachusetts Institute of Technology.*

The ordinary C.I.E. colorspace is affine, so that in general a comparison of distances and angles is impossible. A number of attempts have been made to introduce a metric into this affine space, but none of these attempts has been very successful. The present paper develops a metric, based on the experimental data of Stiles and Crawford[1] for contrast sensitivity and the data recently obtained by MacAdam[2] for color discrimination. It is found that the problem can be divided into two parts which can be handled separately. The MacAdam data are first transformed to a plane of constant helios in the C.I.E. 3-space, and the metric coefficients g_{11} and g_{33} are obtained by fitting analytic expressions to the experimental points. The third metric coefficient g_{22} is determined from the Stiles and Crawford data. The result gives a Euclidian metric 3-space which is in agreement with the data to within the experimental error. The metric is first derived for the special surround used by MacAdam, and is then extended to any surround and expressed in terms of the composite stimulus.[3]

[1] Stiles and Crawford, "The liminal brightness increment for white light for different conditions of the foveal and parafoveal retina," Proc. Roy. Soc. **116B**, 55 (1934).
[2] D. L. MacAdam, "Visual sensitivities to color differences in daylight," J. Opt. Soc. Am. **32**, 247 (1942).
[3] D. E. Spencer, "Adaptation in colorspace," presented at the Summer Meeting of the Optical Society of America, 1942.

18. Specification of Small Chromaticity Differences. D. L. MACADAM, *Kodak Research Laboratories.*

Ellipses consistent with observed standard deviations of color matching can be represented by

$$g_{11}dx^2+2g_{12}dxdy+g_{22}dy^2=1.$$

In this equation, dx and dy represent the differences of the coordinates of the center and any point on the appropriate ellipse, and the coefficients, g_{11}, g_{12}, g_{22}, are functions of position of the center of the ellipse. Contours have been drawn in I.C.I. diagrams representing values of these coefficients consistent with observed ellipses.[1] If dx and dy represent the differences of coordinates of any two colors then the ratio of the chromaticity difference to the corresponding standard deviation is given by

$$(g_{11}dx^2+2g_{12}dxdy+g_{22}dy^2)^{\frac{1}{2}}.$$

According to this formula the pair of yellow (D) lines in the sodium spectrum exhibit a chromaticity difference 3.8 times the standard deviation of color matching, and Planckian radiators at temperatures of 3900°K and 4000°K exhibit about half this difference, specifically 2.1 times the corresponding standard deviation of color matching. Selection of the closest match to a specified chromaticity from any series represented by a smooth locus in the same neighborhood is facilitated by use of a formula for the slope, m', of the line joining the corresponding points, in terms of the slope, m, of the locus.

$$m'=-(g_{11}+mg_{12})/(g_{12}+mg_{22}).$$

For example, the Planckian radiator differing least noticeably from the chromaticity represented by the point ($x=0.3840$, $y=0.3840$) is found to have a temperature of 3940°K. The residual chromaticity difference is 2.3 times the corresponding standard deviation, or about as noticeable as a color temperature difference of 110°K in the same region. Within regions for which g_{11}, g_{12}, g_{22} do not change more than about 25 percent, equally noticeable chromaticity differences may be represented by equal distances in oblique coordinate systems in which increments of x and y are represented by the distances $(g_{11})^{\frac{1}{2}}\Delta x$ and $(g_{22})^{\frac{1}{2}}\Delta y$, and the angle, ω, between the directions of measurement of x and y is given by

$$\cos\omega=g_{12}/(g_{11}g_{22})^{\frac{1}{2}}.$$

When coordinate systems defined in this manner for adjoining regions of chromaticity are joined together appropriately, a curved surface is obtained. Such a surface, which is not developable on a plane, sphere, or other familiar surface, is necessary for equidistant representation of equally noticeable chromaticity differences. The geodesics of this curved surface are the paths involving the least number of noticeable steps between terminal chromaticities. These "shortest" paths do not correspond to straight lines in any plane chromaticity diagram.

[1] D. L. MacAdam, "Visual sensitivities to color differences in daylight," J. Opt. Soc. Am. **32**, 247–274 (1942).

19. Chromaticity Discrimination. ELLIOT Q. ADAMS, *Lamp Development Laboratory, General Electric Company.*

No chromaticity diagram can be strictly of "uniform scale" for two reasons: the differences between individual observers (and between different regions of the same retina) must alter the shape as well as the size of the loci of equally perceptible difference, and the non-linearity of the relation between stimulus and sensation must lead to differences in different parts of the chromaticity field. Colorimetric discrimination measurements made at constant brightness should be plotted on a constant-brightness chromaticity diagram orthogonal with respect to the two chromatic attributes. By means of a conversion net, the chromaticity discrimination data of MacAdam have been replotted on a constant-brightness chromaticity diagram.

Another source of error is the known scotopic residual in the internationally accepted luminosity values upon which the I.C.I. distribution functions are based.

BIBLIOGRAPHY: D. L. MacAdam, J. Opt. Soc. Am. **32**, 271, 254–5 (1942).

20. The Inter-Society Color Council Color Aptitude Test. FORREST LEE DIMMICK, *Hobart College.*

In February of 1940, the Inter-Society Color Council was requested to prepare a test suitable for evaluating workers in industries where an essential requirement is accurate discrimination of small color differences. A test has been devised which meets the original requirements and offers a tool for the study of "color aptitude in other applications." The test consists of matching judgments which require a very fine degree of discrimination. Colored materials for the first part of the test have been made and this part of the test has now been standardized, far enough so that we feel confident of final results. The materials were prepared by Mr. Carl E. Foss from the most permanent substances available. They were held to rigid spectrophotometric standards and are reproducible. The first part of the test utilizes saturation series of two reds which are chosen because they offer diagnostic confusions to color blind subjects. The complete test will include other color dimensions. The test as now constituted has been made up in three degrees of difficulty. A short form serves as a screening test for complete red-green deficiency. An intermediate form diagnoses degrees of color deficiency from low normal through anomalous to complete $R-G$ deficiency. A full form, utilizing all chips is known as the aptitude test. The aptitude test has been standardized on a group of the "general population" consisting of college students, office workers, and semi and unskilled workers, and upon groups of trained color workers in two branches of the textile industry. Two procedures have been standardized; one which requires completion of 40 matches and corrects the score on the basis of the time taken; and one which permits the subject to work on the test for a limited period of time. On the basis of present results, percentile ratings of various scores have been plotted for the "general population" group and for the "color workers" group.

21. Tristimulus Specification of the Munsell Book of Color from Spectrophotometric Measurements. K. L. KELLY, *Research Associate at the National Bureau of Standards, representing the American Pharmaceutical Association,* K. S. GIBSON, *National Bureau of Standards,* AND DOROTHY NICKERSON, *Agricultural Marketing Administration.*

The development of the ISCC–NBS system of color names,[1] based on the standards in the *Munsell Book of Color*,[2] made it necessary to specify the master standards of this book in fundamental terms. Accordingly, spectral reflection curves were run for each of the 421 master standards on the G.E. recording spectrophotometer at the NBS, with use of slit widths of approximately 4 millimicrons. Corrections for wave-length errors, for 100 percent and zero curve deviations, and for aging of the MgO comparison surface, were applied to the data in accordance with methods regularly used for such work.[3] Colorimetric computations were then made with these data, resulting in tristimulus specifications according to the 1931 I.C.I. standard observer and coordinate system and for I.C.I. standard illuminant *C*. Similar colorimetric evaluation of the color standards was also carried out at the Department of Agriculture on automatic punch card machines for I.C.I. illuminants *A* and *C*, for illuminant "*D*" (Macbeth 7500°K) and for illuminant "*S*" (limit blue sky). The colorimetric specifications for all four illuminants will be published in the complete paper. The trilinear coordinates calculated for I.C.I. illuminant *C* have been plotted on large (x, y)-diagrams and constant Munsell chroma lines drawn in. Similar values obtained by Glenn and Killian at Massachusetts Institute of Technology in 1935 for Munsell color standards bearing the same hue-value-chroma designations have also been plotted on these diagrams. Differences between the two sets of data will be illustrated and discussed. These diagrams serve as the means of determining the Munsell notation and thereby the ISCC–NBS color name for any color whose trilinear coordinates and apparent reflectance are given.

[1] D. B. Judd and K. L. Kelly, J. Research Nat. Bur. Stand. **23**, 355 (1939), RP 1239.
[2] *Munsell Book of Color* (Munsell Color Company, Baltimore, 1929).
[3] K. S. Gibson and H. J. Keegan, J. Opt. Soc. Am. **28**, 372 (1938).

22. Tristimulus Specifications for Intermediate and Special Colors of the Munsell System. WALTER GRANVILLE, *Interchemical Corporation Research Laboratories, New York,* DOROTHY NICKERSON, *Agricultural Marketing Administration, USDA, Washington,* AND CARL FOSS, *Color Consultant, New York.*

Approximate identification of color by means of direct visual comparison can be carried out with the 20 standard hues of the 1929 edition of the *Munsell Book of Color*.[1] But many persons who would like to make visual comparisons find it difficult to interpolate for hue when the hue standards are restricted to 20. In order to aid such persons, 20 additional hues have recently been added to the Munsell series of charts, also the /2 chromas missing in the original *Book of Color* charts. In addition to colors for new charts to be inserted with the early series, several special series of "Munsell colors" have been made available for special purposes: a series of 100 hues at 5/5; 50 hues at maxima chroma; a 50-step value scale; a 20-step chroma scale; a series of pinks, of browns. Each of these series becomes more useful when standard I.C.I. colorimetric data become available for it, for the I.C.I. data serve as a calibration for this system of material standards.[2] The authors, over a period of several years, have collected and measured these colors. The 20 new intermediate hues, plus /2 chromas to complete the charts of the 20 standard hues, total 561 colors (in addition to the 421 colors of the standard series). The special series total approximately 350 colors. Spectral apparent reflectance curves were run

on each sample by means of the General Electric Recording spectrophotometer in the Research Laboratories of Interchemical Corporation. Tristimulus values and trilinear coordinates have been determined for I.C.I. illuminant *C*, using the selected ordinate method. Dominant wavelength and purity were obtained from large scale sections of the I.C.I. mixture diagram in the Hardy *Handbook of Colorimetry*.[3] Diagrams will be presented to indicate the relation of the intermediate series to the standard series measured by others.[4,5]

[1] *Munsell Book of Color* (Munsell Color Company, Baltimore, 1929).
[2] American War Standard, Specification and Description of Color. Z44–1942, American Standards Association.
[3] A. C. Hardy, *Handbook of Colorimetry* (Technology Press, 1936).
[4] J. J. Glenn and J. T. Killian, "Trichromatic analysis of the *Munsell Book of Color*," J. Opt. Soc. Am. **30**, 609 (1940).
[5] K. L. Kelly, K. S. Gibson, and Dorothy Nickerson, "Tristimulus specification of the *Munsell Book of Color* from spectrophotometric measurements" (this program), preceding abstract.

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